AERITALIA
società aerospaziale italiana
Space Systems Group

TETHERED GRAVITY LABORATORIES STUDY

CONTRACT NAS 9-17877

NASA LYNDON B. JOHNSON SPACE CENTER

MID-TERM REVIEW

TORINO, ITALY - SEPTEMBER 26-28, 1989

TETHERED GRAVITY LABORATORIES STUDY

MID-TERM REVIEW

ACTIVITIES STATUS

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TASK 1 - ACTIVE C.O.G. CONTROL .... COMPLETED

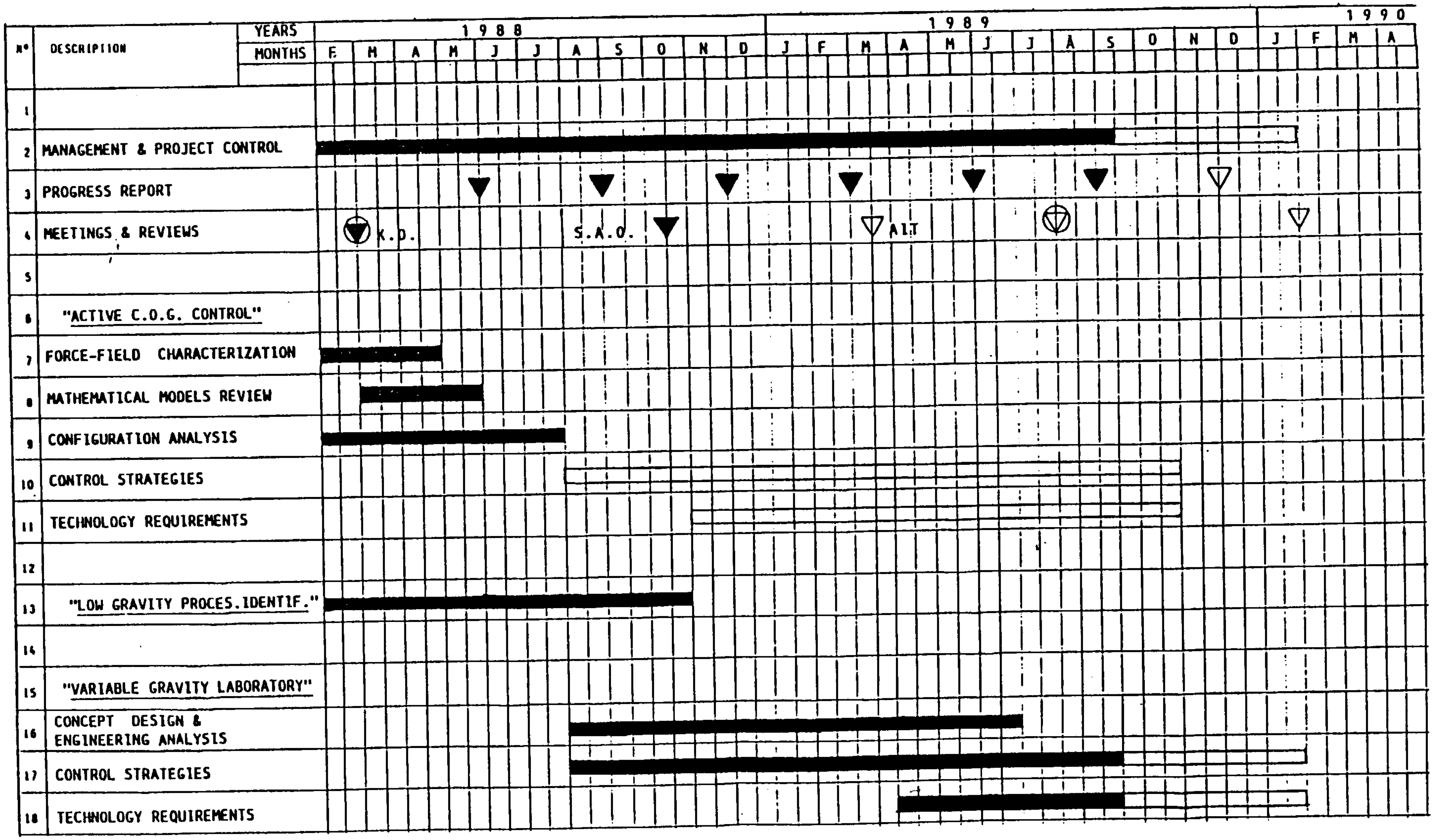
TASK 2 - LOW GRAVITY PROCESSES IDENTIFICATION .... COMPLETED

TASK 3 - VARIABLE GRAVITY LABORATORY

- CONCEPT. DESIGN & ENGIN. ANALYSIS (AIT) .... COMPLETED
- CONTROL STRATEGIES (SAO) .... 70 % COMPLETED
- TECHNOLOGY REQUIREMENTS (AIT) .... 50 % COMPLETED

TASK 4 - ATTITUDE TETHER STABILIZER .... ATP PENDING

ACTIVITIES STATUS - MASTER BAR CHART



ACTIVE C.O.G. CONTROL

STATEMENT OF THE PROBLEM

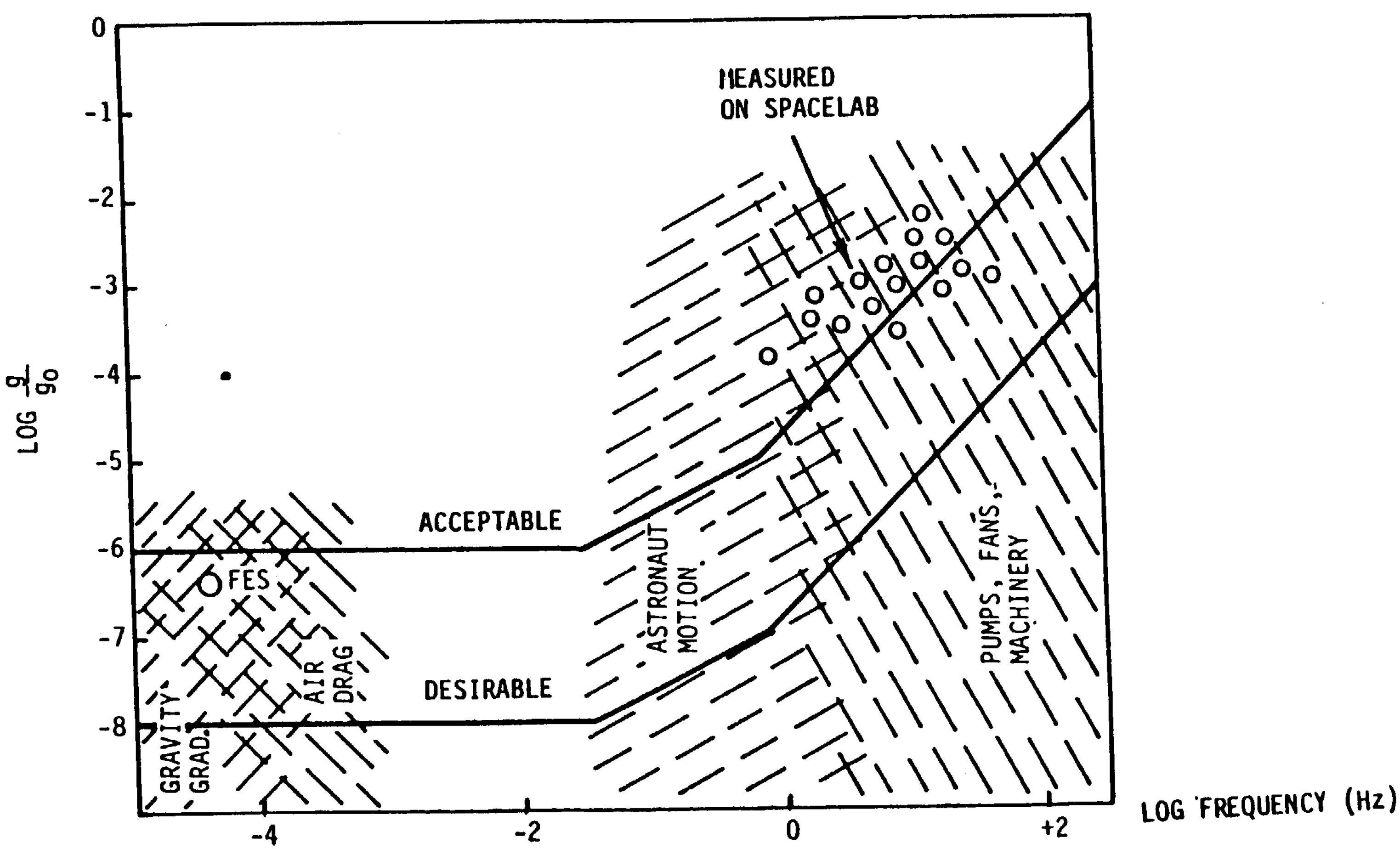
DESIRABLE LIMITS OF ACCELERATIVE FORCES

Dr. R.J. NAUMANN, NASA/MSFC

- SPACELAB MEASURED STEADY ACCELERATIONS ARE 3.8×10^{-7} go
- 10^{-5} go (ISS REQUIREMENT) IS 26 TIMES WORSE AND WILL LIMIT THE USEFULNESS OF SPACE STATION
- TOLERANCE TO TRANSIENT OR PERIODIC ACCELERATIONS INCREASES AS ω^2.
- ADDITIONAL DEVELOPMENT IS NEEDED TO REDUCE EFFECT OF STEADY OR VERY LOW FREQUENCY DISTURBANCES
- "STEADY ACCELERATIONS CAN REALLY KILL YOU IN A LOT OF MICRO-G PROCESSES".

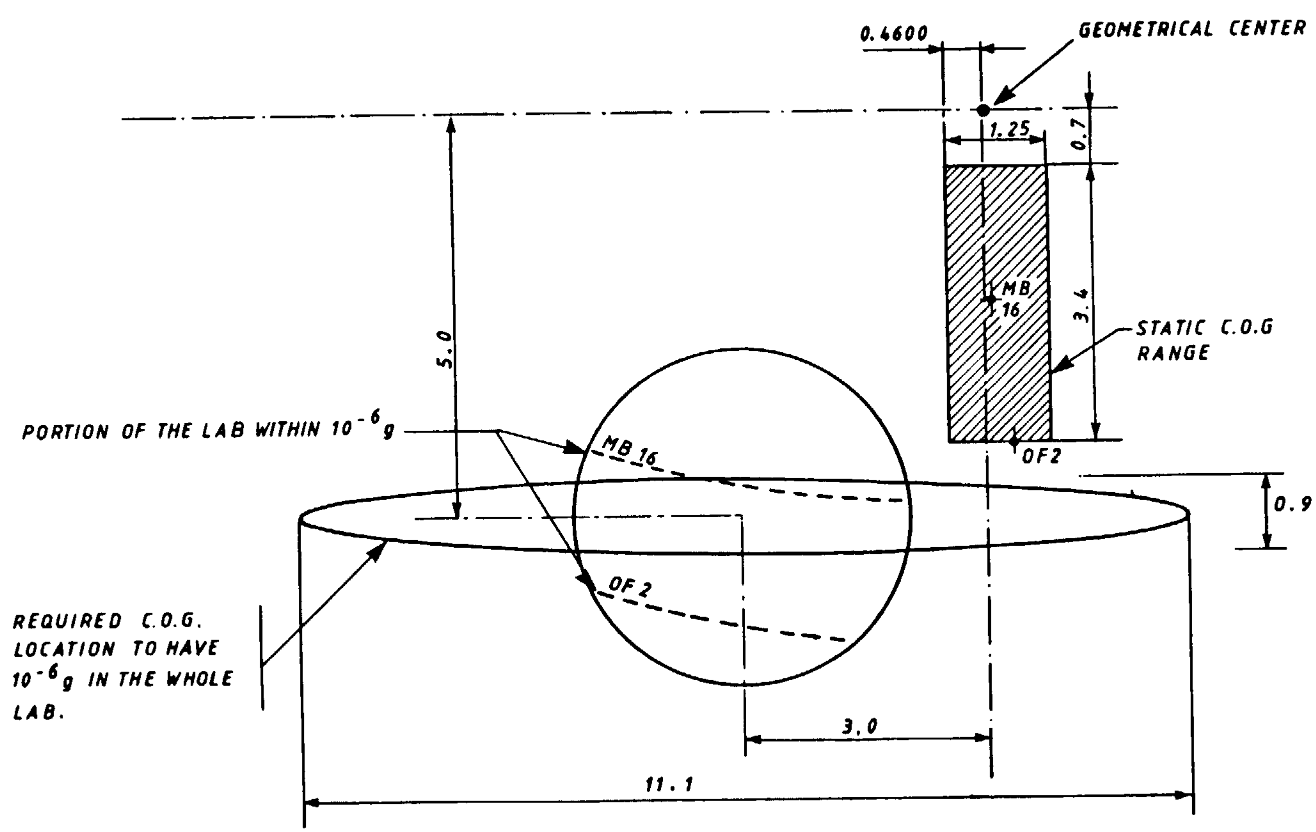
STATEMENT OF THE PROBLEM

NAUMANN PROPOSED ACCELERATION LIMITS



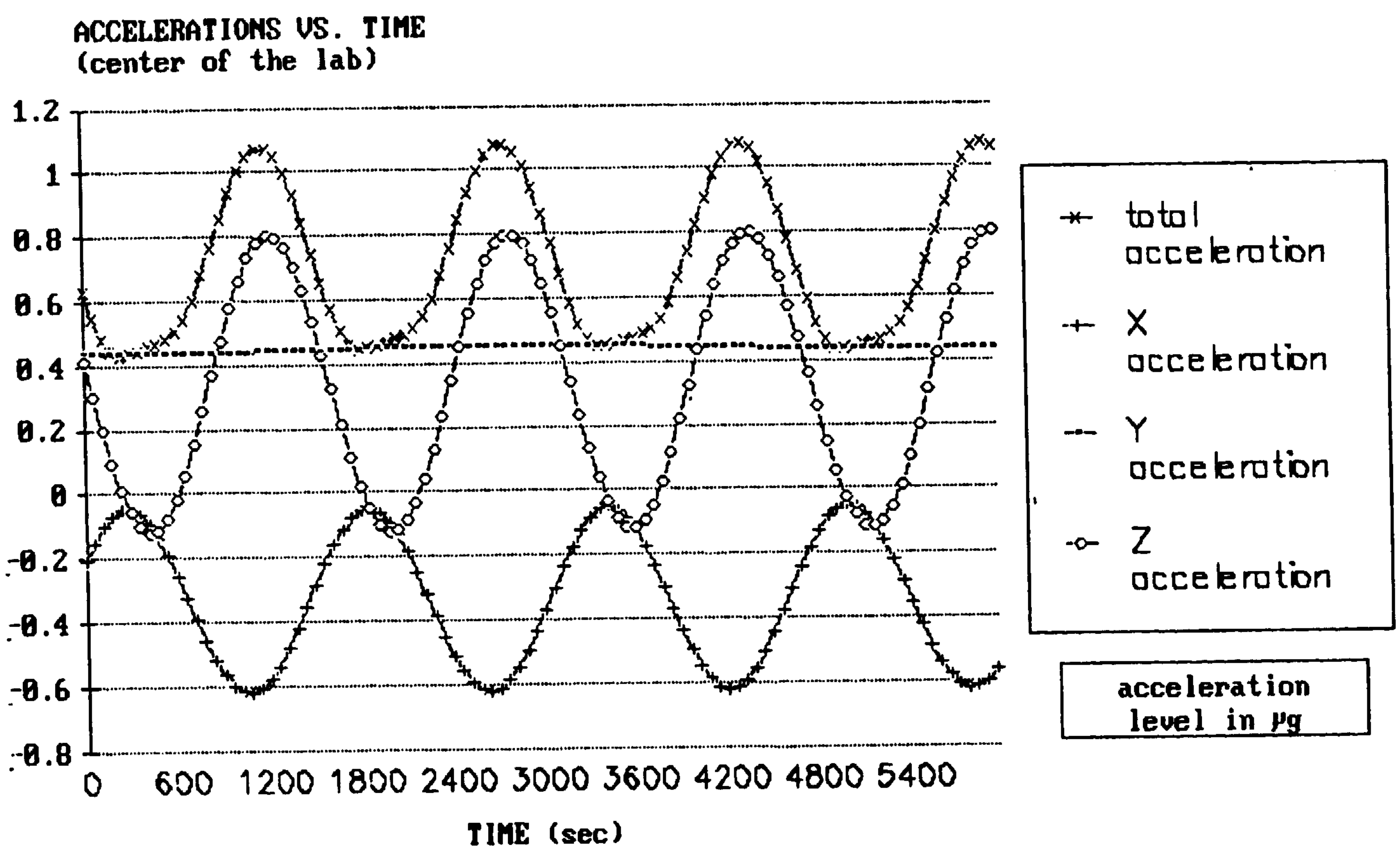
STATEMENT OF THE PROBLEM

GRAVITY GRADIENT 1 MICRO-G ENVELOPES (USA LAB)



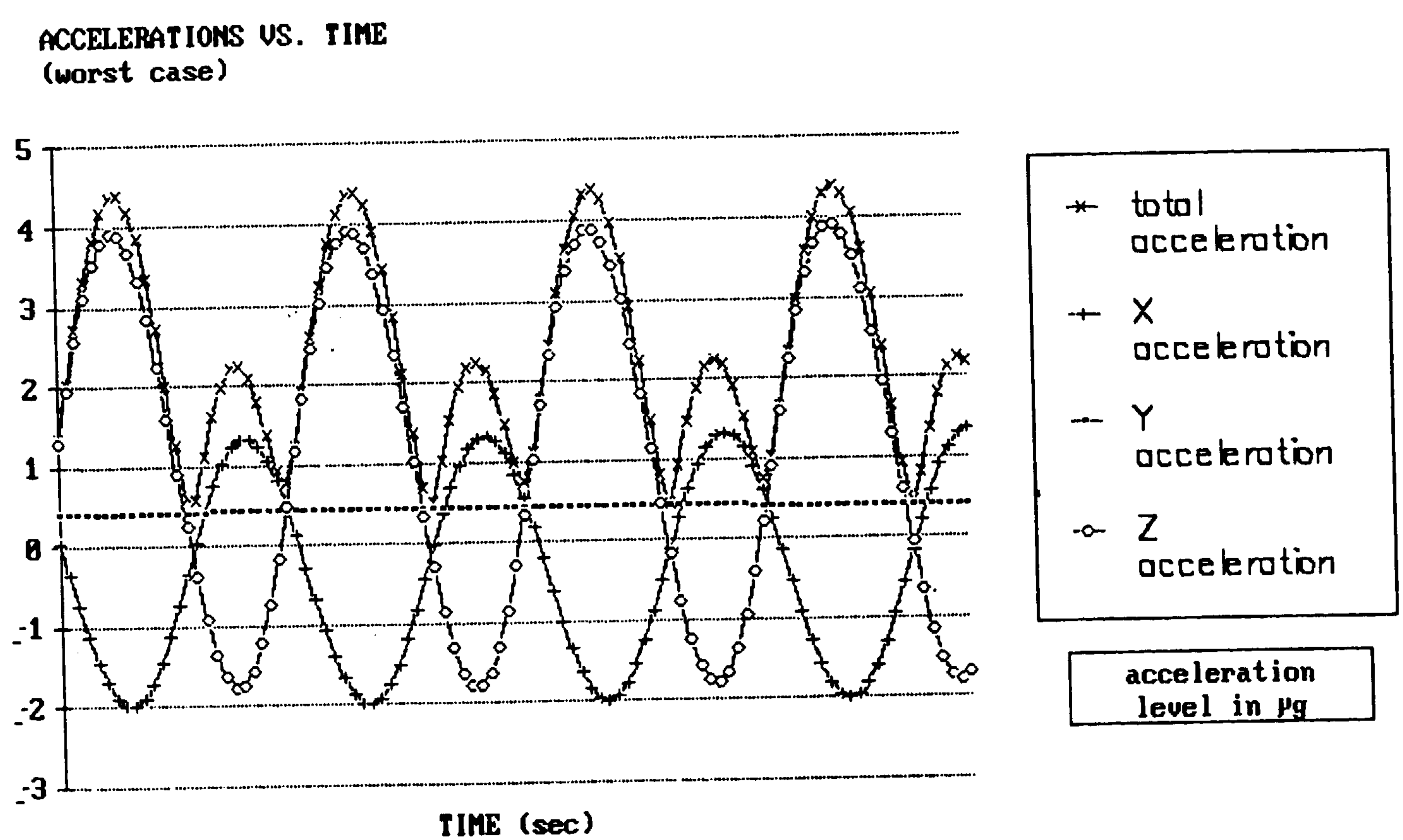
STATEMENT OF THE PROBLEM

PHASE 1 (OF2) ACCELERATIONS DUE TO EXTERNAL SOURCES AND ROTATIONS



STATEMENT OF THE PROBLEM

PHASE 2 (MB16) WORST CASE ACCELERATIONS (COLUMBUS END)



STATEMENT OF THE PROBLEM

ANALYSIS RESTRICTIONS

- o SOLAR INERTIAL POWER SYSTEM FLIGHT MODE WAS NOT CONSIDERED DUE TO LACK OF INFORMATIONS.
  - – VERY LOW FREQUENCY ACCELERATIONS COULD BE INDUCED BY THIS FLIGHT MODE
- o LOW FREQUENCY RANDOM COMPONENTS WERE NOT CONSIDERED DUE TO LACK OF INFORMATIONS ON SPACE STATION INTERNAL DISTURBANCIES
  - – NON PERIODICAL LOW FREQUENCY ACCELERATIONS COULD BE INDUCED BY INTERNAL SOURCES.

STATEMENT OF THE PROBLEM

SUMMARY

- 10^{-6} go ACCEPTABLE STEADY ACCELERATION (10^{-8} go DESIDERABLE)
- IN THE PHASE 1 SPACE STATION STEADY ACCELERATIONS ARE UNDER THE 1 μG LEVEL NEARLY IN THE OVERALL LABS AREA
- IN THE PHASE 2 SPACE STATION STEADY ACCELERATIONS ARE OVER THE 1 μG LEVEL IN THE GREATER AREA OF LABS
- TETHER SYSTEMS CAN ALLOW THE ATTAINMENT OF THE 0.5 μG LEVEL OF STEADY ACCELERATION
- ROTATIONS INDUCED ACCELERATIONS CAN BENEFIT FROM TETHERS PRESENCE, BUT A COMPLETE ANALYSIS OF THE GENERAL ATTITUDE CONTROL PROBLEM IS INVOLVED.

TETHERED C.O.G. CONTROL RATIONALE

C.O.G. SHIFT (ASSUMED TO BE EQUAL TO C.O.M. SHIFT)

- ONE TETHER SYSTEM

$$Z_{COG} = \frac{(M + \frac{1}{2} \mu L) \ L}{(M_S + \mu \ L + M)}$$

- TWO TETHERS SYSTEM

$$Z_{COG} = \frac{(M1 + \frac{1}{2} \mu_1 \ L1) L_1 - (M2 + \frac{1}{2} \ \mu_2 \ L2) \ L2}{(M_S + \mu_1 \ L1 + \mu_2 \ L2 + M1 + M2)}$$

- M_S = STATION MASS
  M = COUNTERWEIGHT MASS
  Z_{COG} = COG SHIFT DUE TO TETHERED SYSTEM
  μ = TETHER LINEAR DENSITY

  M1, L1, $\mu 1$ REFERRED TO DOWNWARD TETHER
  M2, L2, $\mu 2$ REFERRED TO UPWARD TETHER

TETHERED C.O.G. CONTROL RATIONALE

CONSTRAINTS ON ENFORCED TETHER MOTION

- FOR A PERIODICALLY VARYING TETHER LENGTH L

  $L(t) = L_o + L_c \, \mathrm{SIN}(\Omega \cdot t)$

  ϑ = IN-PLANE TETHER ANGLE WITH LOCAL VERTICAL

  $$\vartheta_{MAX} = 2 \frac{L_c \cdot \Omega \cdot n}{L_o \cdot \left(3 n^2 - \Omega^2\right)} \quad \text{(MASSLESS TETHER } L_c \ll L_o\text{)}$$

- A CONSTRAINT ON THE MAX AMPLITUDE OF TETHER LIBRATIONS IMPLIES A CONSTRAINT ON THE VARIATION OF TETHER LENGTH.

  IF $\vartheta_{MAX} < 3^o$ AND $\Omega = n \Rightarrow L_c < L_o / 20$

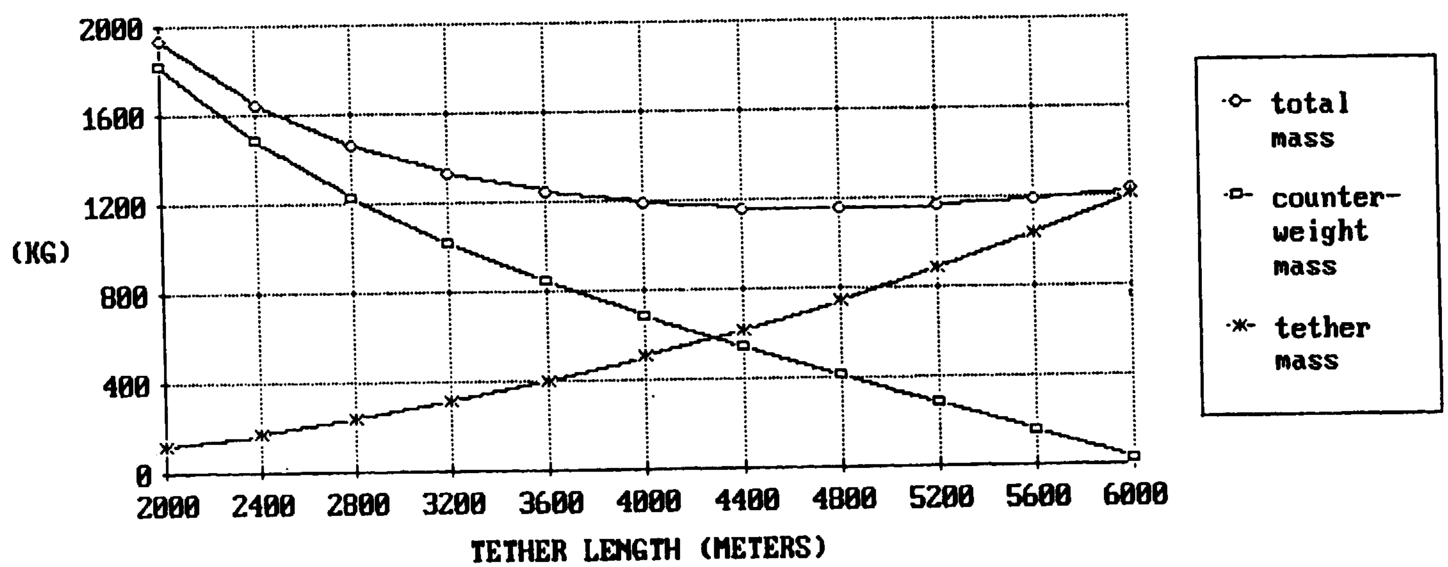
- THE RANGE OF VARIATION OF Z_{COG} IS RELATED TO L_c AND L_o

  $$\Delta Z_{COG} = \frac{2 (M + \mu \cdot L_o) \; L_c}{M_S}$$

TETHERED C.O.G. CONTROL RATIONALE

TETHER AND COUNTERWEIGHT MASS TRENDS AS A FUNCTION OF TETHER LENGTH

DESIRED C.O.G. SHIFT = 15 M   STATION MASS = 250*10^3 KG



CONFIGURATION ANALYSIS

ASSUMPTIONS

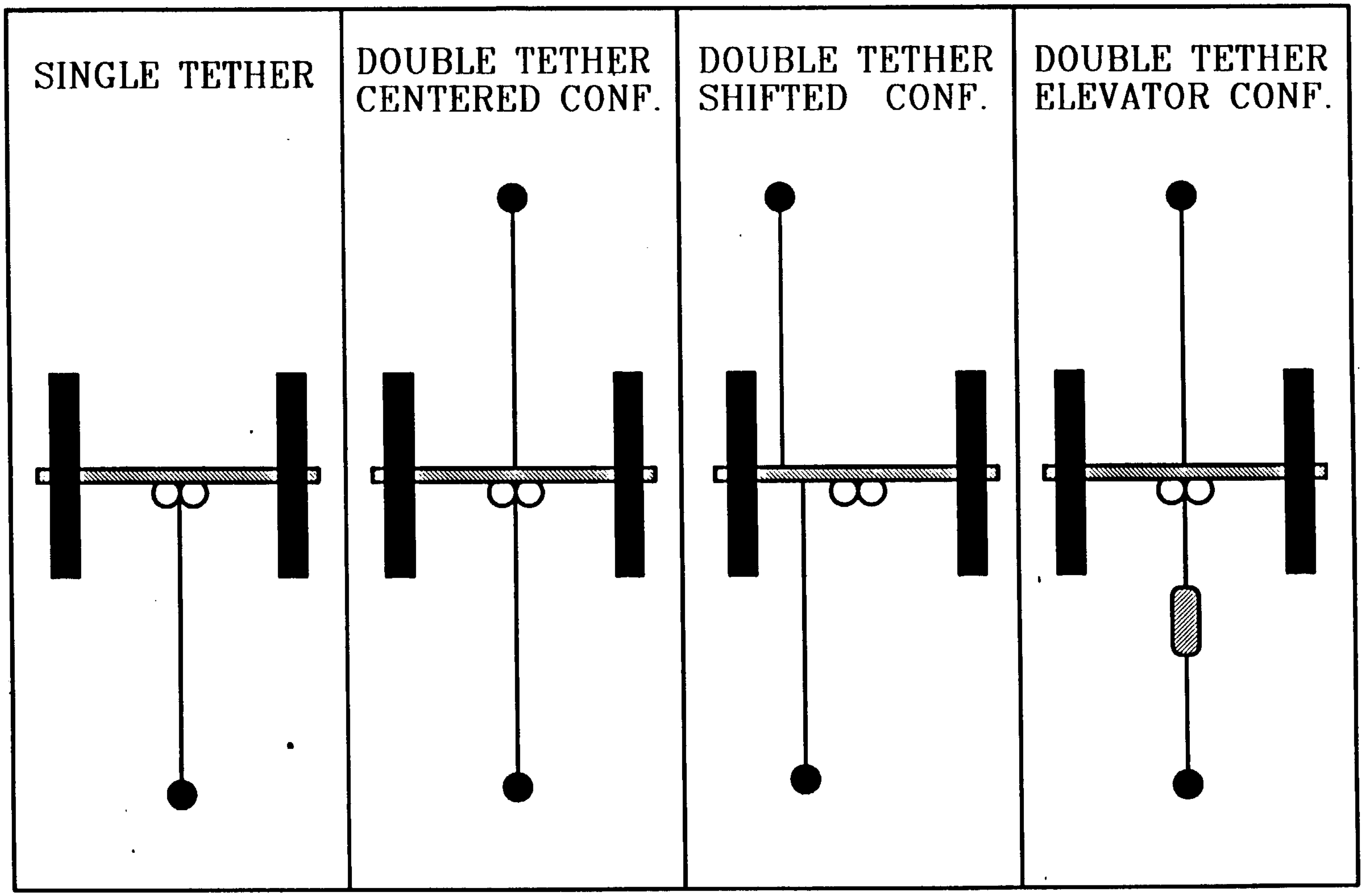
- o DATA ON SPACE STATION

CONFIGURATION	OF2	MB16
MASS (KG)	204.5 10^3	258,8 10^3
Z_{COG} (M)	4.108	2.33

FROM
"PHASED PROGRAM ASSEMBLY
CONFIGURATION DATA"

- o MEAN ORBITAL RATE: 1.14 · 10^{-3} RAD/SEC (366 KM)
- o TETHER SIZE DICTATED BY IMPACT PROBLEMS
- o MAX AMPLITUDE OF TETHER IN PLANE LIBRATIONS: ± 3°
- o DISTURBANCE CHARACTERISTICS: AMPLITUDE ± 5 μG; FREQUENCY = n
- o SYSTEM DIMENSION OPTIMIZED WITH REFERENCE TO SYSTEM MASS AND SIZE
- o TETHER MATERIAL: ALUMINIUM

TETHERED CONFIGURATIONS



CONFIGURATION TRADE-OFF
OVERALL MASS AND LENGTH FEATURES

TET. CONFIGURATION	PHASE I SPACE ST.		PHASE II SPACE ST.	
	TOTAL MASS (KG)	TOTAL LENGHT (m)	TOTAL MASS (KG)	TOTAL LENGHT (m)
SINGLE TETHER	149	1660	365	2766
DOUBLE CENTERED TETHER	12080	14224	14196	15227
DOUBLE SHIFTED TETHER	12080	14224	–	–
DOUBLE TETHER + ELEVATOR	9873	10735	11503	11919

CONFIGURATION ANALYSIS

o SINGLE TETHER	
- STATIC C.G. CONTROL	- LIMITED C.G. RANGE
- LIGHT AND SIMPLE	- CLEARANCE PROBLEMS
o DOUBLE TETHER CENTERED CONFIGURATION	
- STATIC AND DYNAMIC C.G. CONTROL	- CLEARANCE PROBLEMS IN PHASE 1 SS
- MASSIVE AND LARGE FOR DYNAMIC CONTROL	
o DOUBLE TETHER SHIFTED CONFIGURATION	
- APPLICABLE ONLY IN PHASE 1	- REDUCED CLEARANCE PROBLEMS
- COMPLEXITY DUE TO T.A.P. REQUIRED MOBILITY	
o DOUBLE TETHER + ELEVATOR	
- HIGH DYNAMIC STABILITY	- LIMITED DIMENSIONS
- COMPLEXITY DUE TO ELEVATOR PRESENCE	

SPACE STATION IMPACTS

SPACE STATION IMPACTS CLASSIFIED IN FOUR MAIN CATEGORIES:

- o OPERATIONAL
  PROXIMITY MANOEUVRES; RENDEZ-VOUS; REBOOSTING; EVA; TETHER DEPLOYMENT AND RETRIEVAL

- o DISTURBANCES
  THERMOSTRUCTURAL EFFECTS; TETHER LIBRATIONS AND VIBRATIONS; ENVIRONMENTAL FORCE AND TORQUE

- o TETHER SEVERAGE
  TETHER RUPTURE DUE TO METEOROIDS HITS

- o ATTITUDE CONTROL
  - PROBLEM FOR LARGE ATTITUDE MANOEUVRES (IF REQUIRED)
  - STABILIZATION AID AGAINST ENVIRONMENTAL TORQUES.

SPACE STATION IMPACTS

	TETHER SYSTEM CONFIGURATION							
	SINGLE TETHER		DOUBLE CENTERED TETHER		DOUBLE SHIFTED TETHER		DOUBLE TET. + ELEVATOR	
IMPACT CATEGORIES	PHASE I	PHASE II	PHASE I	PHASE II	PHASE I	PHASE II	PHASE I	PHASE II
OPERATIONAL	MEDIUM	LOW	HIGH	MEDIUM	MEDIUM	N.A.	HIGH	MEDIUM
DISTURBANCES	MEDIUM	LOW	HIGH	LOW	MEDIUM	N.A.	HIGH	LOW
TETHER SEVERAGE	MEDIUM	LOW	HIGH	MEDIUM	HIGH	N.A.	HIGH	MEDIUM
ATTITUDE CONTROL (MAY BE BENEFICIAL)	LOW	MEDIUM	HIGH	HIGH	HIGH	N.A.	HIGH	HIGH

CONFIGURATION TRADE-OFF

PHASE I SPACE STATION

- C.O.G. APPEARS TO BE CLOSE ENOUGH FOR THE ATTAINMENT OF 1 μG LEVEL NEARLY IN THE OVERALL LABS AREA
- PERIODIC PERTURBING ACCELERATIONS OF LOW FREQUENCY SEEM TO BE NEAR THE 1 μG MAGNITUDE
- DYNAMIC CONTROL REQUIRES MASSIVE TETHER SYSTEMS
- STRONG CLEARANCE PROBLEMS FOR TETHERED SYSTEMS MOUNTED NEAR THE CORE SPACE STATION
- SINGLE TETHER IS THE ONLY CONFIGURATION LIMITING IMPACTS ON SPACE STATION, BUT ITS USE SEEMS UNNECESSARY.

CONFIGURATION TRADE-OFF

PHASE II SPACE STATION

- STEADY ACCELERATIONS ARE OVER THE 1 μG LEVEL IN THE GREATER AREA OF LABS
- TETHER SYSTEMS CAN ALLOW THE 0.5 μG LEVEL ATTAINMENT
- PHASE II SPACE STATION MORE ADEQUATE FOR TETHER SYSTEMS UTILIZATION
- STATIC TETHER SYSTEM CAN COUNTERACT STEADY ACCELERATIONS EXPECIALLY IF LARGE PAYLOADS ARE PLACED ON THE UPPER BOOM
- DYNAMIC CONTROL REQUIRES QUITE MASSIVE TETHER SYSTEMS.
  C.O.G. CONTROL COULD BE ACCOMPLISHED IN CONJUNCTION WITH OTHER TETHER APPLICATIONS (E.G., TETHERED PLATFORM, ELEVATOR).

CONFIGURATION TRADE-OFF

MAJOR FINDINGS

- TETHER SYSTEMS UTILIZATION FOR C.O.G. CONTROL IN THE PHASE I SPACE STATION DOES NOT PRESENT A SUFFICIENT BENEFIT/COST FIGURE.
- C.O.G. CONTROL MORE SUITABLE FOR APPLICATION IN THE PHASE II SPACE STATION
- MB16 STATIC TETHER SYSTEM (LIGHT AND SIMPLE) COULD BE CONSIDERED FOR FURTHER STUDY ON STEADY ACCELERATIONS CONTROL
- MB16 DOUBLE TETHER SYSTEM FOR DYNAMIC CONTROL SHOULD BE EVENTUALLY CONSIDERED IN CONJUNCTION WITH TETHER PLATFORMS.
- MB16 DOUBLE TETHER + ELEVATOR SYSTEM SHOULD BE EVENTUALLY CONSIDERED IN A LARGE ELEVATOR UTILIZATION SCENARIO.

ACTIVE C.O.G. CONTROL TASK KEY OPTIONS

- OPTION 1

  SELECTION OF TWO CONFIGURATIONS TO BE FURTHER INVESTIGATED.
  RECOMMENDED CONFIGURATIONS: MB16-SINGLE TETHER SYSTEM; MB16-DOUBLE TETHER + ELEVATOR SYSTEM OR DOUBLE TETHER SYSTEM (STATIC CONTROL)

- OPTION 2

  NO FURTHER EFFORT ON THIS CONCEPT.
  REMAINING MAN-HOURS TO INCREASE EFFORT ON VARIABLE GRAVITY LABORATORY AND/OR LOW GRAVITY PROCESSES TASKS.

- OPTION 3

  REMAINING MAN-HOURS TO INVESTIGATE THE USE OF TETHERED SYSTEMS FOR SPACE STATION ATTITUDE STABILIZATION AND CONTROL.

REDIRECTON STATUS

- o NASA-JSC DIRECTION WAS TO ADDRESS A NEW STUDY AREA ACCORDING TO OPTION-3 (OCTOBER 1988).

- o AIT TECHNICAL PROPOSAL WAS SENT TO NASA-JSC (NOVEMBER 1988) ASSUMING FULL REDIRECTION OF AVAILABLE MAN-HOURS.

- o NOW IT IS NEEDED TO CHANGE APPROACH:

  - ONLY FOUR MONTHS TO THE CONTRACT END

- o RECOMMENDATION:

  - PERFORM TETHER STABILIZER ACTIVITIES ACCORDING TO A FOUR MONTHS SCHEDULE

  - UTILIZE REMAINING HOURS TO COVER A MORE DETAILED CONCEPTUAL DESIGN WITHIN VARIABLE GRAVITY LABORATORY TASK

LOW GRAVITY PROCESSES IDENTIFICATION

LOW GRAVITY PROCESSES IDENTIFICATION

TASK ACTIVITY AND RESULTS PRESENTATION: CONTENTS

* STUDY TASK OBJECTIVES
* STUDY TASK APPROACH AND LOGICS
* REVIEW AND INVESTIGATION OF EXPERIMENTAL AREAS
* EXPERIMENTS RELEVANT TO A TETHERED VARIABLE GRAVITY LABORATORY
* REQUIREMENTS ON A VARIABLE GRAVITY LABORATORY
* CONCLUSIVE REMARKS

LOW GRAVITY PROCESSES IDENTIFICATION

STUDY TASK OBJECTIVES

- REVIEW OF THE AREAS OF EXPERIMENTAL INVESTIGATION IN MICROGRAVITY (LIFE SCIENCES AND FLUIDS / MATERIALS SCIENCES)

- IDENTIFICATION OF PROCESSES / EXPERIMENTAL TOPICS SIGNIFICANT TO VARIABLE GRAVITY (WITH EMPHASIS ON STEADY LEVELS)

- DEFINITION OF THE RELATED "GRAVITY PROFILES" (GRAVITY VERSUS TIME CURVES) WITHIN THE REFERENCE RANGE $10^{-6} \div 10^{-1}$ g_0

- GENERATION OF THE REQUIREMENTS CONCERNING THE ACCELERATION ENVIRONMENT OF THE VARIABLE GRAVITY LABORATORY

LOW GRAVITY PROCESSES IDENTIFICATION

ORIGINAL STUDY APPROACH

- REVIEW OF SELECTED LITERATURE ELEMENTS CONCERNING THE EXPERIMENTAL AREAS INVESTIGATED IN MICROGRAVITY
- IDENTIFICATION OF THE BASIC PHYSICAL AND PHYSICO-CHEMICAL PHENOMENA AFFECTED BY THE GRAVITY FIELD
- ASSESSMENT OF THE DEPENDANCE OF THE MENTIONED PHENOMENA ON THE GRAVITY FIELD BY MEANS OF MATHEMATICAL THEORIES (EXCLUDING LIFE SCIENCE PHENOMENA)
- DEFINITION OF THE PROCESSES SIGNIFICANT TO VARIABLE GRAVITY AND OF THE RELATED g-PROFILES, CHECKING THE RESULTS BY MEANS OF THE SCIENTISTS' ADVICE

LOW GRAVITY PROCESSES IDENTIFICATION

PROBLEMS FACED DURING THE COURSE OF THE STUDY

- VERY SCARCE SUGGESTIONS ENCOUNTERED, DURING LITERATURE REVIEW, CONCERNING APPLICATIONS FOR EXPERIMENTATION IN VARIABLE GRAVITY

- MATHEMATICAL THEORIES DESCRIBING g-LEVEL/FREQUENCY DEPENDANCE OF THE INVOLVED PHENOMENA ARE GENERALLY INADEQUATE TO REPRESENT REAL, PRACTICAL EXPERIMENTAL SITUATIONS; IN ADDITION SEVERAL TOPICS ARE NOT COVERED

- VARIABLE GRAVITY ENVIRONMENT IS VERY OFTEN CONSIDERED AS AN APPEALING NOVELTY AND A "POTENTIALLY USEFUL" OPTION TO EXPLOIT, NOT ONLY TO TAILOR "OPTIMAL" CONDITIONS TO THE EXPERIMENTS, BUT ALSO TO EXTEND EXPERIMENTAL INVESTIGATION TO REGIONS WHERE GRAVITY EFFECTS BEGIN TO APPEAR MORE AND MORE STRONG AND EVIDENT (FOR THEORETICAL MODELS VALIDATION, VERIFICATION OF EXTRAPOLATED DATA, CLARIFICATION OF UNCERTAIN FINDINGS, THRESHOLD FIXING,...)

- LOW GRAVITY PROCESS IS MOSTLY INTENDED AS EXPERIMENTAL ACTIVITY, NOT AS (PRE-)INDUSTRIAL PRODUCTION / TECHNOLOGICAL PROCESS

LOW GRAVITY PROCESSES IDENTIFICATION

MODIFICATION OF THE STUDY LOGICS

- MODIFICATION OF THE UNDERSTANDING OF "PROCESS", SINCE THE LARGEST SHARE OF USERS' INTEREST IS FOR A TOOL CAPABLE TO SUPPORT PURE AND APPLIED SCIENTIFIC RESEARCH PERFORMANCE

- ENHANCEMENT OF THE IMPORTANCE OF THE CONTACTS WITH THE SCIENTISTS, AS POTENTIAL USERS OF THE LABORATORY, TO HAVE DIRECT INPUT TO EXPERIMENTAL ENVELOPES AND GOALS DEFINITION

- ACCEPTANCE OF THE PRELIMINARY STATUS OF THE RESULTS OF THE PRESENT SURVEY, DUE TO THE CONTACTED USERS DIFFICULTY TO DEEPLY AND FULLY EVALUATE A COMPLETE WHOLE OF UTILISATION PERSPECTIVES

LOW GRAVITY PROCESSES IDENTIFICATION

CRITICISING THE CONCEPT OF "g-PROFILE"

- A "g-PROFILE", DEFINED AS A CURVE IN THE GRAVITY VERSUS TIME PLANE, IS NOT FELT AS THE BEST DESCRIPTOR OF THE EXPERIMENTAL REQUIREMENTS IN VARIABLE GRAVITY AS IT CANNOT EASILY ACCOUNT FOR THE EFFECT OF THE VARIATION OF ALL THE PARAMETERS (MATERIAL PROPERTIES, GEOMETRIC FACTORS, PHYSICAL VARIABLES) IN THE FORMULAS CORRELATING GRAVITY TO TIME

- BESIDES, IT IS NOT CAPABLE TO REPRESENT THE EXPERIMENTAL APPROACH TO THE ANALYSIS OF A PHENOMENON, WHEN A PARAMETRIC VARIATION OF THE GRAVITY LEVEL IS REQUIRED

- A BETTER DESCRIPTOR IS FOUND IN THE MORE COMPREHENSIVE CONCEPT OF "GRAVITY BAND" RELEVANT TO A CERTAIN EXPERIMENTAL AREA, DEFINING THE LIMITS (MINIMUM AND MAXIMUM LEVELS OF GRAVITY) WITHIN WHICH EXPERIMENTATION IS FELT MEANINGFUL

LOW GRAVITY PROCESSES IDENTIFICATION

REVIEW AND INVESTIGATION OF EXPERIMENTAL AREAS IN MICROGRAVITY

- AREAS OF INTEREST AND OF EXPERIMENTAL ACTIVITY IN MICROGRAVITY TAKEN IN CONSIDERATION:

FLUIDS AND MATERIALS SCIENCES

> FLUID STATICS AND DYNAMICS
> THERMODYNAMICAL AND TRANSPORT PROPERTIES MEASUREMENT
> CRITICAL POINT, PHASE BOUNDARY AND ADSORPTION PHENOMENA
> COMBUSTION
> PHYSICAL, ELECTRO- AND APPLIED CHEMISTRY
> CRYSTAL GROWTH FROM MELT, FROM SOLUTION AND FROM VAPOUR
> PROTEIN CRYSTALLISATION
> METALLURGY (PURE METALS AND ALLOYS), DIRECTIONAL SOLIDIFICATION
> COMPOSITES MATERIALS PREPARATION
> GLASSES PREPARATION
> SEPARATIVE TECHNIQUES (ELECTROPHORESIS, PHASE PARTITIONING)

LIFE SCIENCES

> ANIMAL (INCLUDING HUMAN) PHYSIOLOGY
> PLANT PHYSIOLOGY
> CELL BIOLOGY
> BIOTECHNOLOGY

LOW GRAVITY PROCESSES IDENTIFICATION

FLUID STATICS

EXPERIMENTAL TOPICS

- SHAPE AND STABILITY OF LIQUID MASSES PARTIALLY CONTAINED (E. G. COLUMNS) BOTH STEADY AND ROTATED
- CONTACT ANGLES OF LIQUIDS CONFINED WITHIN SOLID CONTAINERS
- CAPILLARY PHENOMENA (MENISCUS SHAPE AND LEVEL) IN CAPILLARY TUBES AND OTHER CONTAINERS
- INTERFACIAL BEHAVIOUR OF DIFFERENT CONTIGUOUS LIQUID MASSES
- WETTING PHENOMENA CLOSE CRITICAL POINTS
- OSCILLATIONS OF DROPS AND LIQUID BRIDGES IN FUNCTION OF THE FREQUENCY

GRAVITY DEPENDING PHENOMENA

DECREASED/SUPPRESSED ACTION OF WEIGHT AND UNHAMPERED OBSERVATION OF THE EFFECTS OF THE SURFACE/INTERFACE TENSION

LOW GRAVITY PROCESSES IDENTIFICATION

FLUID DYNAMICS

EXPERIMENTAL TOPICS

- OBSERVATION OF ONSET,DEVELOPMENT AND REGIME TRANSITIONS IN THERMOCAPILLARY BULK FLOWS (MARANGONI CONVECTION) INDUCED BY THERMAL / SOLUTAL / THERMOSOLUTAL GRADIENTS
- EFFECTS OF ADDITIONAL STIMULI ON THE ABOVE MOTIONS (ELECTRIC FIELDS)
- FLUID MOTION PHENOMENA UNDER SLOSHING AND BOILING (APPLICATIVE EXPERIMENTS)
- SPREADING KINETICS
- SURFACE INSTABILITIES (WAVES) UNDER THE PREVAILING EFFECT OF SURFACE TENSION
- MIXING AND DEMIXING KINETICS OF DIFFERENT INSOLUBLE LIQUIDS
- MOTION AND INTERACTION OF LIQUID DROPS
- MOTION OF (SOLID, LIQUID, GASEOUS) INCLUSIONS WITHIN LIQUID MATRICES

GRAVITY DEPENDING PHENOMENA

- WEIGHT ACTION SUPPRESSION AND ASSOCIATED SEDIMENTATION BUOYANCY
- GRAVITY DRIVEN CONVECTION REDUCTION/SUPPRESSION AND POSSIBILITY TO OBSERVE THE BY FAR WEAKER THERMAL AND/OR SOLUTAL CONVECTION

LOW GRAVITY PROCESSES IDENTIFICATION

THERMODYNAMICAL AND TRANSPORT PROPERTIES MEASUREMENT, CRITICAL POINT, PHASE BOUNDARY AND ADSORPTION PHENOMENA

EXPERIMENTAL TOPICS

- MEASUREMENT OF THERMODYNAMICAL FUNCTIONS OF CORROSIVE SUBSTANCES
- MEASUREMENT OF PRESSURE, TEMPERATURE AND SPECIFIC VOLUME NEAR THE CRITICAL POINT OF PURE FLUIDS
- EQUILIBRIUM DISTRIBUTION IN A FLUID AT THE CRITICAL POINT
- SEPARATION AT OF BINARY MIXTURES AND SPINODAL DECOMPOSITION
- FLUIDS INTERFACE BEHAVIOUR CLOSE TO THE CRITICAL POINT (WETTING, ADSORPTION,...)
- BOILING / NUCLEATION PHENOMENA AND PHASE TRANSITIONS

GRAVITY DEPENDING PHENOMENA

- AVOIDANCE OF COLLAPSING OF THERMODYNAMIC TEST VOLUME UNDER ITS OWN WEIGHT
- SUPPRESSION OF SEDIMENTATION AND BUOYANCY, PREVENTING FROM PROPER CONFIGURATION STABILITY
- SUPPRESSION OF TEMPERATURE GRADIENT DRIVEN BUOYANT CONVECTION

LOW GRAVITY PROCESSES IDENTIFICATION

COMBUSTION, PHYSICAL CHEMISTRY, CHEMICAL KINETICS AND RELAXATION PHENOMENA

EXPERIMENTAL TOPICS

- COMBUSTION OF MIXED AND UNPREMIXED FLAMES
- COMBUSTION OF LIQUIDS (DROPLETS)
- FLAME SPREADING ALONG SOLID FUEL SURFACES
- PROPAGATION OF WAVES OF CHEMICAL ACTIVITY
- CHEMICAL REACTIONS AND PROCESSES
- ELECTROLYSIS AND APPLIED ELECTROCHEMISTRY EFFECTS
- RELAXATION IN MOLTEN SALTS AFTER ABSORPTION OF ULTRASONIC WAVES

GRAVITY RELATED PHENOMENA

- AVOIDANCE OF CONVECTIVE MOTIONS AND BUOYANCY PHENOMENA DISTURBING PURELY DIFFUSIVE HEAT / MASS TRANSFER

LOW GRAVITY PROCESSES IDENTIFICATION

CRYSTAL GROWTH FROM MELT

EXPERIMENTAL TOPICS

- PRODUCTION OF CRISTALLINE MATERIALS BY SOLIDIFICATION FROM A LIQUID PHASE - THE MELT - WHICH IS THE SAME SUBSTANCE OF THE CRYSTAL

- USUALLY, THE FOLLOWING TECHNIQUES ARE USED:

  > DIRECTIONAL SOLIDIFICATION OF MELTS IN AMPOULES, UNDER A SHIFTING GRADIENT OR MOVING THE SAMPLE UNDER A FIXED GRADIENT

  > FLOATING ZONE CRYSTALLISATION, FOCUSING RADIATION IN A MIRROR FURNACE ON A MOVABLE BAR-SHAPED SAMPLE

GRAVITY RELATED PHENOMENA

- HYDROSTATIC PRESSURE ABSENCE IN THE MELT ZONE

- AVOIDANCE OF STEADY AND UNSTEADY BUOYANT CONVECTION EFFECTS (MACRO- AND MICRO-SEGREGATION)

LOW GRAVITY PROCESSES IDENTIFICATION

CRYSTAL GROWTH FROM SOLUTION

EXPERIMENTAL TOPICS

- PRODUCTION OF CRYSTALS OBTAINED BY GRADUAL INCORPORATION ON A SEED OF A SOLUTE WHICH IS TRANSPORTED THROUGH THE SOLUTION UP TO THE SURFACE OF THE GROWING CRYSTAL
- DIFFERENT PRODUCTION PROCESSES ACCORDING TO THE MATERIALS:
  - HIGH TEMPERATURE PROCESSES (FLUX GROWTH, GROWTH FROM METALLIC SOLUTION)
  - LOW TEMPERATURE PROCESSES (LOW SOLUBILITY AND HIGH SOLUBILITY MATERIALS)
- PROTEIN CRYSTALLISATION IS ACHIEVED IN A LIQUID SOLUTION (E. G.: COUNTER-DIFFUSION OF A PROTEIN SOLUTION AND OF A SALT SOLUTION INTO A LIQUID BUFFER)

GRAVITY RELATED PHENOMENA

- CRYSTAL'S OWN WEIGHT ELIMINATION
- THERMAL BUOYANCY CONVECTION SUPPRESSION (PURE HEAT / MASS DIFFUSION CONDITIONS)
- PROTEINS: GRAVITY DRIVEN CONVECTION TURBULENCE SUPPRESSION

LOW GRAVITY PROCESSES IDENTIFICATION

CRYSTAL GROWTH FROM VAPOUR

EXPERIMENTAL TOPICS

- PRODUCTION OF CRYSTALS BY TRANSPORT OF THE NUTRIENT SUBSTANCE IN VAPOUR PHASE TO THE GROWING INTERFACE, ACCORDING TO DIFFERENT TECHNIQUES:
  - PHYSICAL VAPOUR TRANSPORT (VAPOUR OF THE VOLATILE SUBSTANCE)
  - CHEMICAL VAPOUR TRANSPORT (NON VOLATILE SUBSTANCES, CHEMICAL REACTION WITH A TRANSPORT AGENT)
  - CHEMICAL VAPOUR DEPOSITION (NON VOLATILE SUBSTANCES, DEPOSITION FROM A GASEOUS REACTANT)

GRAVITY RELATED PHENOMENA

- CRYSTAL'S OWN WEIGHT SUPPRESSION
- SUPPRESSION OF THERMAL CONVECTION INSTABILITIES

LOW GRAVITY PROCESSES IDENTIFICATION

METALLURGY: METALS AND MISCIBLE ALLOYS

EXPERIMENTAL TOPICS

- PRODUCTION OF METALS AND METALLIC ALLOYS BY SOLIDIFICATION FROM THE LIQUID STATE, OBTAINING A CRISTALLINE STRUCTURE, CONCERNING:
  - CASTING
  - DIRECTIONAL SOLIDIFICATION (SOLIDIFICATION FRONT SEGREGATION, MORPHOLOGICAL STABILITY, DENDRITIC GROWTH, UNDERCOOLING, NUCLEATION)

GRAVITY RELATED PHENOMENA

- ELIMINATION OF THERMAL / SOLUTAL BUOYANT CONVECTION EFFECTS FROM THE HEAT / MASS TRANSPORT MECHANISMS

LOW GRAVITY PROCESSES IDENTIFICATION

METALLURGY: IMMISCIBLE ALLOYS AND COMPOSITES

<u>EXPERIMENTAL TOPICS</u>

- PRODUCTION OF METALLIC ALLOYS DUE TO SOLIDIFICATION OF SYSTEMS SHOWING A MISCIBILITY GAP IN THE LIQUID PHASE, WITH ATTENTION TO:
  - NUCLEATION PHENOMENA
  - GROWTH OF THE NUCLEATED DROPS
- PRODUCTION OF COMPOSITE MATERIALS, CHARACTERISED BY A MACROSCOPICALLY HETEROGENEOUS MIX OF OF TWO SOLID PHASES, BY SOLIDIFICATION FROM THE LIQUID PHASE (AT LEAST OF ONE), INCLUDING:
  - IN SITU COMPOSITES (EUTECTIC, PERITECTIC, MONOTECTIC SYSTEMS)
  - ARTIFICIAL COMPOSITES

<u>GRAVITY RELATED PHENOMENA</u>

- SUPPRESSION OF DESTABILISING EFFECTS OF GRAVITY DRIVEN THERMAL CONVECTION
- SUPPRESSION OF BUOYANCY / SEDIMENTATION

LOW GRAVITY PROCESSES IDENTIFICATION

GLASSES PREPARATION

EXPERIMENTAL TOPICS

- PRODUCTION OF BOTH METALLIC AND NON METALLIC SUBSTANCES UNDER THE GLASSY STATE
- HETEROGENEOUS NUCLEATION CONTRIBUTION SUPPRESSION BY AVOIDING THE CONTACT OF THE FACILITY WALLS WITH THE FUSED PORTION OF GLASS
- SEVERAL CONCEPTS OF CONTAINERLESS FACILITIES (ACOUSTIC, AERODYNAMIC, ELECTROSTATIC, ELECTROMAGNETIC LEVITATION AND POSITIONING)

GRAVITY RELATED PHENOMENA

- WEIGHT ABSENCE
- SUPPRESSION OF THERMAL CONVECTION

LOW GRAVITY PROCESSES IDENTIFICATION

SEPARATIVE PROCESSES: ELECTROPHORESIS, PHASE PARTITIONING

EXPERIMENTAL TOPICS

- TECHNIQUES EMPLOYED TO ENHANCE THE SEPARATION EFFICIENCY OF BIOLOGICAL MATERIALS SUCH AS CELLS AND PROTEINS AND THE PURITY OF THE SEPARATED FRACTIONS:
  - CONTINUOUS FLOW ELECTROPHORESIS
  - ISOELECTRIC FOCUSING ELECTROPHORESIS
  - PHASE PARTITIONING

GRAVITY RELATED PHENOMENA

ELECTROPHORESIS: SUPPRESSION OF FRICTION GENERATED THERMAL GRADIENT CONVECTION

PHASE PARTITIONING: AVOIDANCE OF BUOYANCY PHENOMENA

LOW GRAVITY PROCESSES IDENTIFICATION

ANIMAL (INCLUDING HUMAN) PHYSIOLOGY

EXPERIMENTAL TOPICS

- OBSERVATION AND ANALYSIS OF THE INFLUENCE OF THE ABSENCE OF TERRESTRIAL GRAVITY ON MAN AN ANIMALS, AT LEVEL OF:
    - RESPIRATORY SYSTEM
    - CARDIOVASCULAR AND METABOLIC SYSTEM
    - MUSCOSKELETAL SYSTEM
    - NEUROPHYSIOLOGY
- HEALTH CARE AND MAINTENANCE, PHARMACOLOGICAL AIDS

GRAVITY RELATED PHENOMENA

- FLUID REDISTRIBUTION AND ASSOCIATE EFFECTS ON BARORECEPTORS
- LOSS OF COMPETITIVE EFFECT OF WEIGHT ON MUSCLES, BONES, ORGANS

LOW GRAVITY PROCESSES IDENTIFICATION

PLANT PHYSIOLOGY

EXPERIMENTAL TOPICS

- OBSERVATION AND STUDY OF GRAVITROPISM: MODIFICATIONS IN PLANT GROWTH, REPRODUCTION AND SURVIVAL MECHANISMS DUE TO THE REDUCTION / LACK OF GRAVITY FORCE:
    - SEED GERMINATION
    - SMALL PLANT GROWTH AND MORPHOLOGY
    - PROTOPLAST PHYSIOLOGY
- CLOSED ECHOSYSTEMS

GRAVITY RELATED PHENOMENA

- INHIBITION OF GRAVIRECEPTORS (AMYLOPLASTS) FUNCTION DUE TO SUPPRESSION OF BUOYANCY / SEDIMENTATION

LOW GRAVITY PROCESSES IDENTIFICATION

CELL BIOLOGY

EXPERIMENTAL TOPICS

- INVESTIGATION OF THE BEHAVIOUR OF BIOLOGICAL CELLS UNDER ABSENCE OF WEIGHT AS A BASIC SUBJECT AND TO ACHIEVE A BETTER UNDERSTANDING OF COMPLEX ORGANISMS AND SYSTEMS, INCLUDING SUCH AREAS AS:
    - MICROBIOLOGY
    - MAMMALIAN CELL BIOLOGY
    - UNICELLULAR BIOLOGY
    - EMBRIOLOGY

GRAVITY RELATED PHENOMENA

- CELL MORPHOLOGY CHANGES DUE TO LOSS OF THEIR OWN WEIGHT
- INFLUENCE ON GRAVIRECEPTORS
- DIRECT MOLECULAR INTERACTIONS OF GRAVITY

LOW GRAVITY PROCESSES IDENTIFICATION

BIOTECHNOLOGY

EXPERIMENTAL TOPICS

- BIOTECHNOLOGICAL CELLS MANIPULATION IN ABSENCE OF WEIGHT:
  - CELL CULTIVATION IN CONTROLLED AND CONSTANT ENVIRONMENT
  - TESTING BACTERIA RESISTANCE TO ANTIBIOTICS
  - VARYING CELL INTERACTION MECHANISMS (ELECTRO-CELL-FUSION)

GRAVITY RELATED PHENOMENA

- CELL CULTIVATION: AVOIDANCE OF DIFFERENT DENSITY CELL SEPARATION (SEDIMENTATION)
- ELECTRO-CELL-FUSION: CELL MORPHOLOGY CHANGES EXPLOITATION

LOW GRAVITY PROCESSES IDENTIFICATION

RELEVANCE OF A TETHERED GRAVITY LABORATORY TO THE EXPERIMENTAL AREAS

- AFTER THE LITERATURE REVIEW PHASE A VERY LIMITED AMOUNT OF INDICATIONS WAS FOUND:

    - POSSIBLE APPLICATIONS OF VARIABLE GRAVITY ARE DISCUSSED IN VERY FEW REFERENCES, USUALLY IN GENERIC OR HYPOTHETICAL FORM

    - THEORETICAL ANALYSES GIVE LIMITED SUPPORT TO THE PURPOSE

- A CAMPAIGN OF DIRECT CONTACTS WITH THE COMMUNITY INVOLVED IN MICROGRAVITY EXPERIMENTATION WAS THUS UNDERTAKEN, IN ORDER TO RECEIVE DIRECT SUGGESTIONS "FROM THE SOURCE" BY THE PEOPLE INVOLVED IN THE RESEARCH LOOP ABOUT THE "REAL" EXPERIMENTAL NEEDS RELEVANT TO VARIABLE GRAVITY

    - A CHOICE OF A SIGNIFICANT NUMBER OF REPRESENTATIVE SCIENTISTS WAS MADE, WITH A SUITABLE DISTRIBUTION OVER THE EXPERIMENTAL CLASSES

    - AT THE END OF THE PHASE, A TOTAL OF 33 EUROPEAN MICROGRAVITY USERS WERE CONTACTED (BY PHONE, LETTER OR MEETINGS):
      9 IN FLUID SCIENCES
      14 IN MATERIALS SCIENCE
      10 IN LIFE SCIENCES.

LOW GRAVITY PROCESSES IDENTIFICATION

FLUID STATICS AND DYNAMICS

- ONLY "POSSIBLE" INTEREST IS ELICITED IN APPLIED FLUID MECHANICS PROBLEMS (FLUID DISTRIBUTION AND SLOSHING IN TANKS, ...)

- GREAT INTEREST IS ASCERTAINED FOR BASIC SCIENTIFIC ISSUES, E.G.:
  - > LIQUID(S) / SOLID CONTACT ANGLES AND HYSTERESIS ASSESSMENT
  - > TRANSITION FROM BUOYANT TO MARANGONI (SURFACE TENSION DRIVEN) CONVECTION (CONVECTIVE MOTION ONSET, MOTION STABILITY, ...)
  - > PERTURBING EFFECTS AND RELAXATION OF JITTER EFFECTS ON VELOCITY FLOW, THERMAL, SOLUTAL FIELDS IN LIQUIDS, WITH OR WITHOUT SECONDARY INCLUSIONS

- STEADY LEVELS ARE REQUIRED UP TO $10^{-2}\ g_0$

LOW GRAVITY PROCESSES IDENTIFICATION

THERMODYNAMICS AND CRITICAL POINT PHENOMENA

- HIGH POTENTIAL INTEREST IS ASCERTAINED IN THIS AREA; A PREFERENCE IS GIVEN TO THE RANGE FROM 10^{-4} TO 10^{-6} g_0

- VARIABLE GRAVITY IS JUDGED A PROMISING TOOL
  - > TO STUDY GRAVITY DEPENDANCE OF ULTRASONIC WAVE ADSORPTION IN MOLTEN SALTS, BY TREATING GRAVITY AS A PARAMETER
  - > TO DISCUSS PHYSICAL MODELS DESCRIBING CRITICAL POINT PHENOMENA, SPINODAL DECOMPOSITION AND RELATED PHASE SEPARATION KINETICS
  - > TO REPEAT ALREADY PERFORMED HEAT TRANSFER AND BOILING POINT EXPERIMENTS UNDER DIFFERENT CONDITIONS

TRANSPORT PROPERTIES MEASUREMENT

- NO NEED FOR VARIABLE GRAVITY IN DIFFUSION OR SORET EFFECT EXPERIMENTS IS EVIDENTIATED, AS JUST THE AVOIDANCE OF (THERMAL OR SOLUTAL GRADIENTS DRIVEN) CONVECTIVE MOTIONS DUE TO BUOYANCY IS REQUESTED, NOT TO SPOIL THE EXPERIMENTAL CONFIGURATION

LOW GRAVITY PROCESSES IDENTIFICATION

PHYSICAL CHEMISTRY, APPLIED CHEMISTRY

- THE LITTLE NUMBER OF EXPERIMENTS PERFORMED UP TO NOW IN THESE AREAS HAMPERS A PRECISE DEFINITION OF EXPERIMENTAL AIMS TO VARIABLE GRAVITY

- PARAMETRIC VARIATION OF GRAVITY LEVELS APPEARS HOWEVER A POSSIBLY USEFUL TOOL TO FUTURE ACTIVITIES

COMBUSTION

- EXPERIMENTAL ACTIVITY CONCERNING SOLID, LIQUID, GASEOUS SUBSTANCES COMBUSTION IS FELT BENEFITING FROM REPETITION OF EXPERIMENTAL SEQUENCES AT DIFFERENT STEADY LEVELS, WITHIN THE RANGE 10^{-1} TO 10^{-4} g_0

  > IT IS PROPOSED TO TEST COMBUSTION PHYSICAL MODELS VALIDITY IN REGIONS WHERE BOTH CONVECTIVE AND DIFFUSIVE HEAT AND MASS TRANSPORT CONTRIBUTIONS TO THE CHEMICAL REACTION KINETICS EXIST, IN ORDER TO COMPARE THEM

LOW GRAVITY PROCESSES IDENTIFICATION

CRYSTAL GROWTH FROM VAPOUR

- VARIABLE GRAVITY IS CONSIDERED A VALID TOOL TO DEFINE THE OPTIMAL GROWTH CONDITIONS FOR THE CRYSTALS, REQUIRING PERIODS UP TO A FEW WEEKS, AND STEADY GRAVITY LEVELS WITHIN 10^{-2} TO 10^{-5} g_0

- A VERY GOOD CONTROL OF THE REMAINING PHYSICAL CONDITIONS (SUCH AS TEMPERATURES, PRESSURE, CONCENTRATIONS,...) IS SUGGESTED AS A FACT OF PARAMOUNT IMPORTANCE, NOT TO MASK GRAVITY DEPENDING RESULTS

- JITTER EFFECTS ANALYSIS IS DISCOURAGED

CRYSTAL GROWTH FROM SOLUTION

- GRAVITY STEADY LEVELS BETWEEN 10^{-2} AND 10^{-4} g_0 CAN PERMIT:
  - > TO STUDY OPTIMAL GROWTH CONDITIONS LINKED TO THE AMOUNT OF CONVECTION RATES TO THE GROWTH INTERFACE
  - > TO ANALYSE THE EFFECTS OF SUPERSATURATION JUMPS RELATED TO SPONTANEOUS NUCLEATION IN THE LIQUID PHASE AND SUBSEQUENT DEFECT CREATION

- g-JITTER EFFECT IS ALSO PROPOSED AS AN EXPERIMENTAL OBJECTIVE

LOW GRAVITY PROCESSES IDENTIFICATION

CRYSTAL GROWTH FROM MELT

- VALIDATION OF DIFFERENT PHYSICAL MODELS CONCERNING THE PROCESS OF GROWTH AND THE STUDY OF PARAMETRICAL GRAVITY DEPENDANCE OF SUCH TOPICS AS:

  > SEGREGATION AND SOLUTAL FIELD SHAPE IN THE MELTED PORTION OF THE SAMPLE (ALSO g-JITTER EFFECTS IS LOOKED FOR)

  > LATERAL SEGREGATION, AS DEPENDING ON THE GRAVITY VECTOR DIRECTION

- THE FULL REFERENCE RANGE OF g LEVELS IS CONSIDERED USEFUL (PRELIMINARY ESTIMATE) TO EXPLORE REGIONS WITH INCREASING BUOYANT CONVECTION PRESENCE

PROTEIN CRYSTALLISATION

- PROTEIN CRYSTALLISATION SHOWED NO DARK AREAS FOR INVESTIGATION IN VARIABLE GRAVITY, AS ONLY THE ESTABLISHMENT OF A PURELY DIFFUSIVE MASS TRANSPORT REGIME IS REQUIRED, TOGETHER WITH AVOIDANCE OF MIXING OF DIFFERENT DENSITY PHASES

LOW GRAVITY PROCESSES IDENTIFICATION

METALLURGY AND COMPOSITES

- METALLURGY IS POTENTIALLY INTERESTED BY VARIABLE GRAVITY, EVEN IF THE COMPLEXITY OF SOLIDIFICATION PHENOMENA, ADDED TO THE VARIATION OF g LEVEL, COULD BRING TO DIFFICULT ANALYSIS OF EXPERIMENTAL RESULTS

- INTERESTING SUBJECTS ARE HOWEVER JUDGED:

  > MORPHOLOGICAL STABILITY, AS A FUNCTION OF DIFFERENT PARAMETERS, INCLUDING GRAVITY LEVEL AND GRAVITY DIRECTION RESPECT TO THE GROWING SOLID/LIQUID INTERFACE

  > ANALYSIS OF PHYSICO-CHEMICAL EFFECTS LINKED TO THE INTERFACE TENSION

  > EXTENSION OF SOLIDIFICATION EXPERIMENTS TO CONVECTO-DIFFUSIVE AND CONVECTIVE REGIONS

- COMPOSITE MATERIALS PRODUCTION IN SPACE SHOWS SOME DARK AREAS AND SOME UNCERTAIN RESULTS (DUE TO COMPLEX INTERACTION OF PHYSICAL AND PHYSICO-CHEMICAL EFFECTS): IT IS FELT THAT EXPERIMENTATION UNDER PARAMETRISED GRAVITY LEVEL CAN HELP CLARIFICATION

- ON THE WHOLE, THE FULL CONSIDERED RANGE IS CONSIDERD BENEFICIAL (10^{-6} TO 10^{-1} g_0)

LOW GRAVITY PROCESSES IDENTIFICATION

GLASSES PREPARATION

- POSSIBILITIES TO EXPLOIT VARIABLE GRAVITY ARE DEFINED RATHER REMOTE

- NO DARK AREAS TO INVESTIGATE WERE SINGLED OUT

- AVOIDANCE OF CONTACTS OF THE MELTED SAMPLE WITH THE CONTAINER WALLS (ACHIEVED BY MEANS OF THE CONTAINERLESS TECHNIQUE) AND OF CONVECTION PHENOMENA ARE SAID SUFFICIENT

SEPARATIVE TECHNIQUES

- NO NEEDS WERE EVIDENTIATED TO PERFORM EXPERIMENTS AT DIFFERENT GRAVITY LEVELS: ELECTROPHORESIS RECEIVES NO BENEFITS AS ONCE THE BUOYANT CONVECTION PHENOMENA ARE SUPPRESSED, INTERNAL FLOW PATHS ARE UNDISTURBED

LOW GRAVITY PROCESSES IDENTIFICATION

ANIMAL (INCLUDING HUMAN) PHYSIOLOGY

- INTRINSIC PROBLEMS EXIST DUE TO THE DIFFICULT / IMPOSSIBLE PROLONGED MOTIONLESS STAY OF LIVING BEINGS AND TO INTERNAL VITAL FUNCTIONS POLLUTION OF "PURE" g-LEVEL
- FIRST GRAVITY LEVEL DECADE (10^0 TO 10^{-1} g_0) WHICH INTERESTING FOR ARTIFICIAL GRAVITY AND THRESHOLD DETERMINATION IS NOT ACCESSIBLE TO VARIABLE GRAVITY LABORATORY

PLANT PHYSIOLOGY

- GRAVITROPISTIC RESPONSES ARE MORE EASILY STUDIED BY MEANS OF CENTRIFUGES WITHIN $10^{-1} \div 10^{-4}$ g_0
- A TETHERED LABORATORY COULD TURN OUT USEFUL WITHIN THE RANGE $10^{-4} \div 10^{-6}$ g_0, A RANGE WHICH IS DEFINED FOR FUTURE INVESTIGATION

LOW GRAVITY PROCESSES IDENTIFICATION

CELL BIOLOGY AND BIOTECHNOLOGY

- NO NEEDS FOR A CONTINUOUS VARIATION OF GRAVITY OVER TIME ARE EXPRESSED, FOR THE TIME BEING
- SPACE CENTRIFUGES ARE SUFFICIENT TO PRESENT NEEDS
- THRESHOLDS DETERMINATION IS NOT POSSIBLE IN THE FIRST DECADE ($10^0 \div 10^{-1}\ g_0$)
- AN ALTERNATIVE POSSIBLE EXPLOITATION OF THE TETHERED LABORATORY IS ENVISAGED TO HOST EXOBIOLGY/RADIOBIOLOGY EXPERIMENTS, BY EXPOSING SAMPLES TO OTHERWISE UNACCESSIBLE EARTH'S ATMOSPHERIC REGIONS
- USES FOR BIOTECHNOLOGY ARE NOWADAYS UNPREDICTABLE

LOW GRAVITY PROCESSES IDENTIFICATION

RESULTS SUMMARY

- VARIABLE GRAVITY IS FAVOURABLY CONSIDERED AS A COMPLEMENTARY RESEARCH TOOL TO "FIXED" GRAVITY EXPERIMENTATION, MAINLY IN FLUIDS AND MATERIALS SCIENCE

- A LIMITED INTEREST IS SHOWN IN LIFE SCIENCES: TETHERED BASED INVESTIGATIONS ARE NOT RELEVANT OR MORE EASILY ACHIEVABLE BY MEANS OF OTHER SYSTEMS (E.G.: CENTRIFUGES)

- MAJOR BENEFITS ARE: DEFINITION OF OPTIMAL GRAVITY CONDITIONS FOR EACH EXPERIMENT KIND AND ACCELERATION TOLERABILITY THRESHOLDS IDENTIFICATION; PARAMETRIC SCANNING OF BROAD G-RANGES FOR PHYSICAL MODELS VALIDATION; DATA EXTENSION / EXTRAPOLATION CHECK; INVESTIGATION OF UNCLEAR PHENOMENA; UNEXPLORED EXPERIMENTAL REGIONS EXAMINATION

- CONSTANT (STEADY) GRAVITY LEVELS ARE BY FAR PREFERRED RESPECT TO "STEPWISE" OR CONTINUOUSLY TIME DEPENDENT GRAVITY "PROFILES"

- "CLEAN" JITTER / NOISE EFFECT STUDY IS ALSO RECOMMENDED, PARTICULARLY IN FLUIDDYNAMICS, IN CRYSTAL GROWTH AND IN METALLURGY

- THE CONCEPT OF GRAVITY BAND PROVED TO BE AN EFFECTIVE DESCRIPTOR OF THE USERS' REQUIREMENTS (AS FAR AS STEADY LEVELS ARE CONSIDERED)

IRI finmeccanica

TETHERED GRAVITY LABORATORIES STUDY

LOW GRAVITY PROCESSES IDENTIFICATION

SYNOPSIS OF THE RESULTS - 1

EXPERIMENT CLASSES	benefit from variable gravity teth.lab	prefe-rred utili-sation option	useful g-level band (g/g_o)	experi-ment duration (order of magnitude)
FLUID STATICS & DYNAMICS	Y	S,J	$10^{-2}\div10^{-6}$	up to hours
THERMODYNAMICS & CRITICAL POINT PHENOMENA	Y	S	$10^{-4}\div10^{-6}$	hours
TRANSPORT PROPERTIES	N	=	=	=
PHYSICAL CHEMISTRY	Y(TBV)	S	TBD	hours(TBV)
COMBUSTION	Y	S	$10^{-1}\div10^{-4}$	min÷hours
CRYSTAL GROWTH FROM VAPOUR	Y	S	$10^{-2}\div10^{-5}$	up to weeks
CRYSTAL GROWTH FROM SOLUTION	Y	S,J	$10^{-2}\div10^{-5}$	days
PROTEIN CRYSTALLISAT.	N	=	=	=
CRYSTAL GROWTH FROM MELT	Y	S,J	$10^{-1}\div10^{-6}$	hours to days
METALLURGY: METALS, ALLOYS AND COMPOSITES	Y	S,J	$10^{-1}\div10^{-6}$	hours to days
GLASSES	N	=	=	=
SEPARATIVE TECHNIQUES	N	=	=	=
ANIMAL PHYSIOLOGY	N	=	=	=
PLANT PHYSIOLOGY	P	S	$10^{-4}\div10^{-6}$	days to weeks
CELL BIOLOGY	N/(*)	(*)	N/A	TBD
BIOTECHNOLOGY	P(TBV)	S(?)	TBD	TBD

NOTES: Y = yes; N = no; P = possible;
S = steady levels; J = jitter or vibration response;
TBD = to be defined; TBV = to be verified
(*) : benefits from variable gravity lab are a quite remote possibility; exo- and radio-biology are possible.

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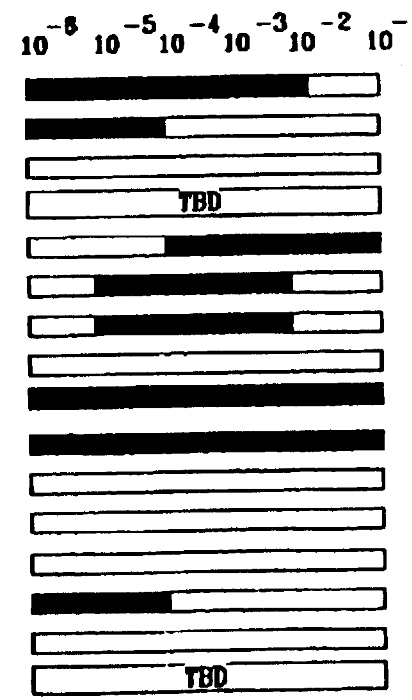
TORINO, 26-28.09.89

LOW GRAVITY PROCESSES IDENTIFICATION

SYNOPSIS OF THE RESULTS - 2

EXPERIMENTAL AREAS	EXPECTED BENEFITS AND KIND OF USE (S= STEADY LEVEL) (J= JITTER ANALYSIS)	USEFUL G-LEVEL BANDS (g/g_{Earth})
FLUID STATICS & DYNAMICS	YES / S, J	
THERMODYNAMICS	YES / S	
TRANSPORT PROPERTIES	NONE	
PHYSICAL CHEMISTRY	YES (TBV) / S	TBD
COMBUSTION	YES / S	
CRYSTAL GROWTH FROM VAPOUR	YES / S	
CRYSTAL GROWTH FROM SOLUTION	YES / S, J	
PROTEIN CRYSTALLISATION	NONE	
CRYSTAL GROWTH FROM MELT	YES / S, J	
METALLURGY (INCL. COMPOSITES)	YES / S, J	
GLASSES (CONTAINERLESS PROC.)	NONE	
SEPARATIVE TECHNIQUES	NONE	
ANIMAL PHYSIOLOGY	NONE	
PLANT PHYSIOLOGY	POSSIBLE / S	
CELL BIOLOGY	ONLY FOR EXO-& RADIOBIOLOGY, TBV	
BIOTECHNOLOGY	POSSIBLE, TBV	TBD



LOW GRAVITY PROCESSES IDENTIFICATION

PRELIMINARY VARIABLE GRAVITY LABORATORY REQUIREMENTS - 1

- EXPERIMENTAL FACILITIES GROUPING IN THE SAME MISSION IS DISCOURAGED DUE TO REASONS OF AVOIDANCE OF MUTUAL INTERFERENCES, BETTER RESOURCES EXPLOITATION IN TERMS OF DIAGNOSTICS AND STIMULI, ...)

- THE ENVELOPE OF g-LEVEL REQUIREMENTS FOR ALL THE EXPERIMENTS CLASSES FILLS THE REFERENCE RANGE: $10^{-6} \div 10^{-1}$ g_0

- DISCRETE STEADY g-LEVELS AVAILABLE ON THE TETHERED LAB SHOULD BE SPACED BY NO MORE THAN HALF A DECIMAL ORDER OF MAGNITUDE (10^{-6}, $5 \cdot 10^{-6}$, 10^{-5} g_0 ETC)

- THE PROVISION OF A g JITTER / NOISE GENERATION DEVICE IS REQUIRED (TO BE DEFINED WHETHER BY THE LABORATORY OR BY EACH SINGLE EXPERIMENT)

- NO EXPLICIT REQUIREMENTS ARE GIVEN FOR THE TIME BEING ABOUT TIME DEPENDENT VARIABLE GRAVITY (IN LEVEL OR DIRECTION)

- DUE TO REASONS OF EQUITABLE SHARING OF THE OPERATIVE TIME BETWEEN THE EXPERIMENTS IT IS SUGGESTED THAT THE MAXIMUM DURATION OF EACH EXPERIMENTAL RUN IS LIMITED TO 15 DAYS

VARIABLE GRAVITY LABORATORY

CONCEPT DEFINITION

VARIABLE GRAVITY

- SEVERAL MICROGRAVITY DISCIPLINES REQUIRE IMPROVEMENT OF G-LEVEL QUALITY AND CLEANLINESS CONSIDERED POSSIBLE ON THE STATION

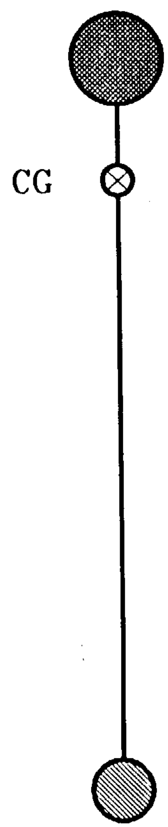
- SEVERAL APPLICATIVE STUDIES POINT OUT THE INADEQUACY OF A CONSTANT LEVEL OF MICROGRAVITY

- INITIALLY, VARIABLE GRAVITY IS SUGGESTED TO INVESTIGATE PHENOMENA AND TO DEFINE THRESHOLD EFFECTS AT DIFFERENT STEADY LEVELS

- VARIABLE GRAVITY IS A NEW OPPORTUNITY, PRODUCTION ORIENTED OR TIME VARYING GRAVITY PROCESSES WILL BE DEFINED AFTER PHENOMENA UNDERSTANDING

CONCEPT DEFINITION

GRAVITY GRADIENT ACCELERATION



366 KM LEO

CG DISTANCE	ACCELERATION
0	0
2.56 M	10−6 G
25.6 M	10−5 G
256 M	10−4 G
2.56 KM	10−3 G
10 KM	0.39*10−2 G

- GRAVITY GRADIENT ACCELERATION ALONG A DEPLOYED TETHER SYSTEM DEPENDS FROM CG DISTANCE
- PLACING A LABORATORY AT PROPER DISTANCE FROM CG IT IS POSSIBLE TO COVER A WHOLE RANGE OF G LEVELS
- A LABORATORY PLACED EXACTLY ON CG CAN IN PRINCIPLE REACH A VERY LOW MICRO-G LEVEL

CONCEPT DEFINITION

VGL UTILIZATION SCENARIO

- o VGL AS DUAL CAPABILITY FACILITY

- o VGL FOR VARIABLE GRAVITY
  - RANGE FROM 10-6 TO 10-2 G
  - UNIQUE CAPABILITY OFFERED BY VGL

- o VGL FOR GOOD QUALITY MICRO-G
  - BETTER ACCESS THAN "COORBITING PLATFORMS"
  - IMPROVED CLEANLINESS DUE TO DISTANCE FROM STATION
  - AVAILABILITY OF SPACE STATION RESOURCES
  - MINIMUM HUMAN INTERVENTION

CONCEPT DEFINITION

ACCESS TIME VS. CAPABILITY FOR MICRO-G FACILITIES

	ACCESS TIME		
	SHORT	*MEDIUM*	*LONG*
POOR MICRO-G QUALITY	*SPACE STATION*		
MEDIUM MICRO-G QUALITY		*VARIABLE GRAVITY LAB.*	*COORBITING PLATFORMS*
VARIABLE GRAVITY LEVEL			

CONCEPT DEFINITION

PRELIMINARY REQUIREMENTS

- G RANGE : FROM 10-6 TO 10-2 G
  - SCIENCE REQUIREMENT TO ACHIEVE 10-1 G IS NOT VIABLE REQUIRING 256 KM TETHER
- G-PROFILE COMPOSED BY A NUMBER OF DISCRETE G-LEVELS (ONE EVERY HALF DECADE)
- 10% ERROR MARGIN ON THE NOMINAL G VALUE
- REQUIREMENTS ON G VECTOR DIRECTION AND STABILITY TO BE DETERMINED
- EXPERIMENT DURATION UP TO 15 DAYS PER LEVEL

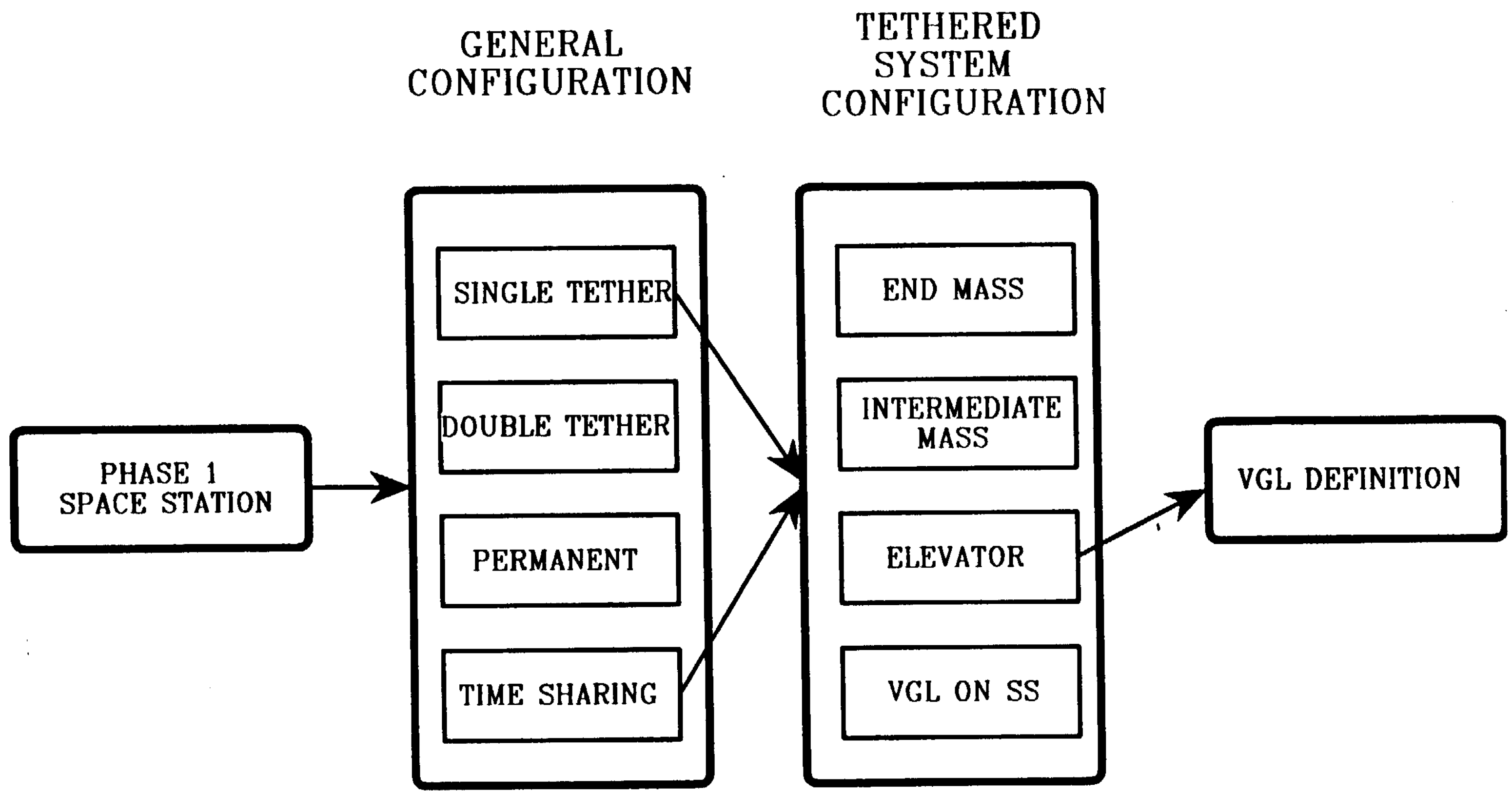
CONFIGURATIONS EVALUATION

CHOICE LEVELS

- o PHASE-1 SPACE STATION SCENARIO WAS ASSUMED
  - THIS IS A MORE PROBLEMATIC SCENARIO FOR TETHERS THAN PHASE-2
- o SPACE STATION/TETHER SYSTEM LEVEL
  - NUMBER AND POSITION OF TETHERS
  - VGL AS PERMANENT OR TEMPORARY FACILITY
- o TETHERED SYSTEM LEVEL
  - END MASS
  - INTERMEDIATE MASS
  - ELEVATOR
  - VGL ON SPACE STATION

CONFIGURATIONS EVALUATION

VGL CONFIGURATION CHOICE LOGICAL FLOW



CONFIGURATIONS EVALUATION

SPACE STATION LEVEL CONFIGURATION CHOICE

DOUBLE TETHER VGL

- A DOUBLE TETHER VGL SYSTEM MAKES SENSE AS A PERMANENT FACILITY OF SPACE STATION

- THE SECOND TETHER IS REQUIRED IN ORDER TO REDUCE THE TIME DURING WHICH 10 MICRO-G REQUIREMENT ON STATION IS VIOLATED

- A SOPHISTICATED SYSTEM IS REQUIRED TO CONTROL SIMULTANEOUSLY BOTH TETHERED SYSTEMS

- A NUMBER OF CONSTRAINTS ON EVA, RENDEZ-VOUS AND REBOOSTING MANOEUVRES ARE GENERATED. A SHIFTED SYSTEM IS POSSIBLE , BUT THIS SOLUTION PRESENTS A VERY HIGH DEGREE OF COMPLEXITY

CONFIGURATIONS EVALUATION

SPACE STATION LEVEL CONFIGURATION CHOICE

SINGLE TETHER VGL

- A SINGLE TETHER VGL SYSTEM HAS TO BE A TEMPORARY DEPLOYED FACILITY IN ORDER TO LIMIT THE TIME DURING WHICH THE MICRO-G REQUIREMENT ON STATION IS VIOLATED

- THE G LEVEL ON THE STATION IS WORSENED DURING THE TEMPORARY VGL USE DEPENDING ON MAX G LEVEL AND VGL MASS

- OPERATIONAL CONSTRAINTS ARE REDUCED AND LIMITED IN TIME

- SINGLE TETHER VGL IS MORE SIMPLE BOTH IN IMPLEMENTATION AND OPERATION ALTHOUGH MORE DEPLOYMENT AND RETRIEVAL OPERATIONS ARE REQUIRED

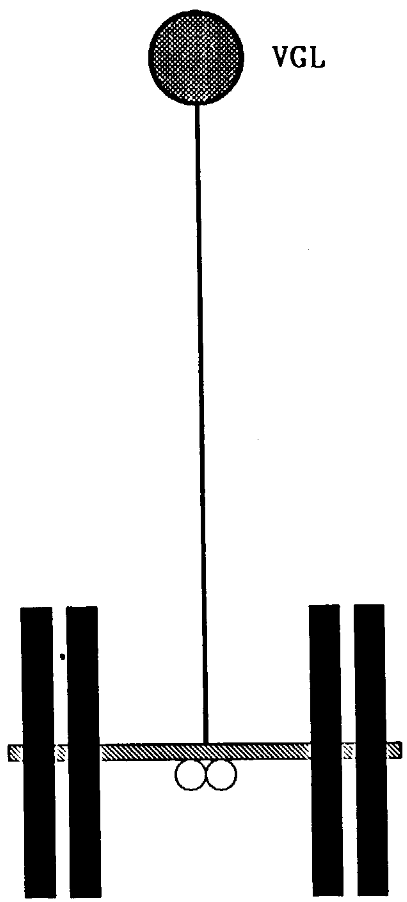
CONFIGURATIONS EVALUATION

CHOICE RATIONALE

- PHASE-1 WAS SELECTED FOR EARLY IMPLEMENTATION OF VGL
- VGL HAS TO BE SEEN AS AN ADDED CAPABILITY TO STATION MICROGRAVITY
- VGL HAS TO BE UTILISED ONLY WHEN REQUIRED FOR A LIMITED TIME
- VGL HAS NOT TO BE CONSIDERED DISRUPTIVE OF STATION MICROGRAVITY BEING THE MICROGRAVITY EXPERIMENT AT THAT TIME
- LIMITATION OF OPERATIONAL CONSTRAINTS AND SYSTEM COMPLEXITY IS HIGHLY DESIRABLE IN PHASE-1 SPACE STATION
- SINGLE TIME-SHARING VGL TETHER SYSTEM IS SUGGESTED AS SUITABLE SOLUTION FOR VARIABLE GRAVITY IN PHASE-1 SPACE STATION

CONFIGURATIONS EVALUATION

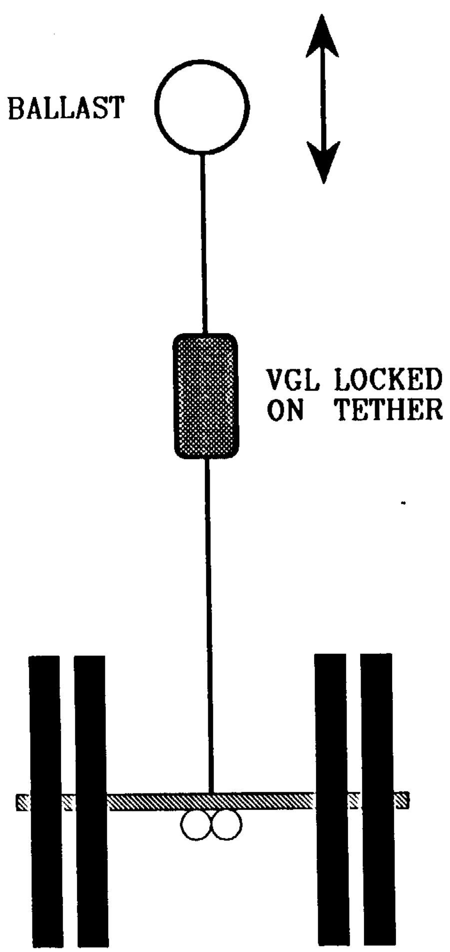
END MASS



- o VGL IS THE END MASS OF TETHERED SYSTEM
- o VARIABLE GRAVITY BY VARYING TETHER LENGTH
- o IMPOSSIBILITY TO ACHIEVE LOW G LEVELS (CG ON TETHER, NEVER ON VGL)
- o DYNAMICAL DISTURBANCES HIGHER THAN OTHER OPTIONS (VARIATION OF TETHER LENGHT TO CHANGE G LEVEL)

CONFIGURATIONS EVALUATION

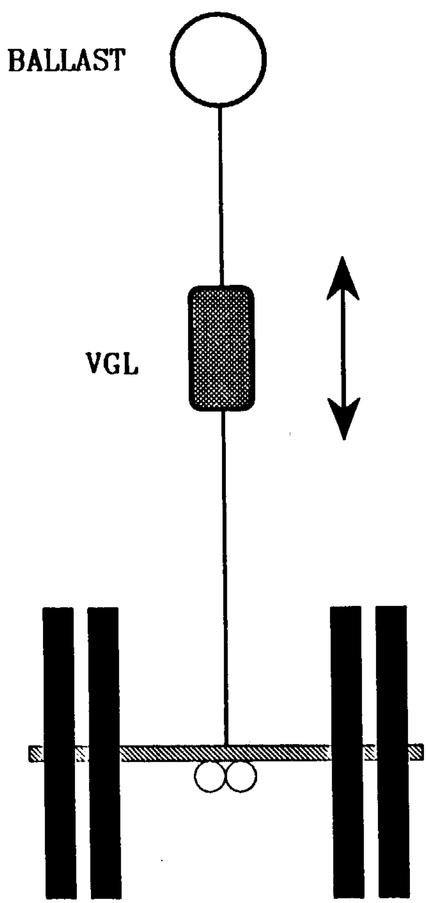
INTERMEDIATE MASS



- VGL IS A MASS RIGIDLY CONNECTED TO AN INTERMEDIATE POINT OF TETHER
- VARIABLE GRAVITY BY VARYING TETHER LENGTH
- ATTACHMENT/DETACHMENT OF VGL DURING DEPLOYMENT/RETRIEVAL OF THE SYSTEM
- DYNAMICAL DISTURBANCES DUE TO VARIATION OF TETHER LENGTH TO CHANGE G LEVEL
- INEFFICIENCY IN THE TETHER USE (TWICE TETHER LENGTH RESPECT ELEVATOR OPTION)

CONFIGURATIONS EVALUATION

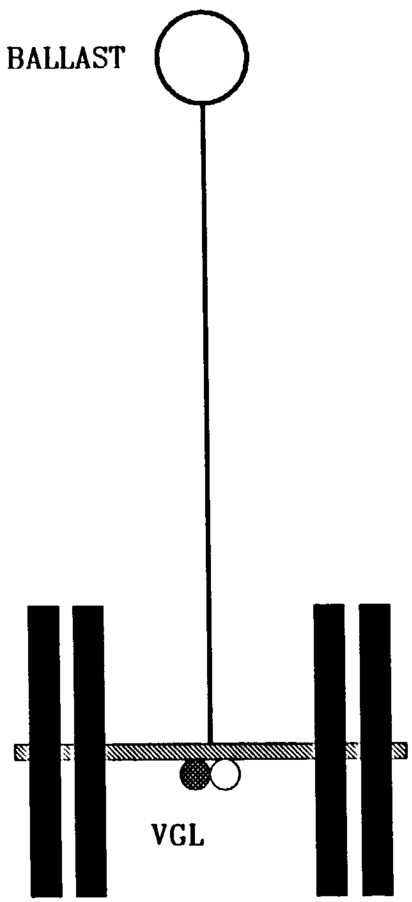
ELEVATOR



- o VGL IS A MASS ABLE TO MOVE ALONG A TETHER OF CONSTANT LENGTH
- o VARIABLE GRAVITY BY VARYING VGL POSITION
- o ATTACHMENT/DETACHMENT OF VGL BEFORE DEPLOYMENT/RETRIEVAL OF END MASS
- o LIMITED DYNAMICAL DISTURBANCES DUE TO THE CONSTANT TETHER LENGTH
- o SYSTEM IS SIMPLE ENOUGH TO BE IMPLEMENTED AND COMPLEX ENOUGH TO BE FLEXIBLE

CONFIGURATIONS EVALUATION

VGL ON SPACE STATION



- o VGL IS ON THE SPACE STATION
- o VARIABLE GRAVITY BY VARYING TETHER LENGTH
- o G LEVEL RANGE LIMITED DUE TO STATION MASS COMPARED TO FEASIBLE BALLAST MASS
- o HIGH INEFFICIENCY IN THE TETHER CAPABILITIES UTILIZATION

CONFIGURATIONS EVALUATION

VGL CONFIGURATIONS MAIN FEATURES

	END MASS	INTERMEDIATE MASS	ELEVATOR	VGL ON SPACE STATION
LOW G	NO	YES	YES	YES
HIGH G	YES	YES	YES	NO
LOW NOISE	YES	YES	YES	NO
SYSTEM COMPLEXITY	LOW	AVERAGE	AVERAGE TO HIGH	LOW
TETHER LENGTH	AVERAGE	HIGH	AVERAGE	HIGH

CONFIGURATIONS EVALUATION

SUMMARY

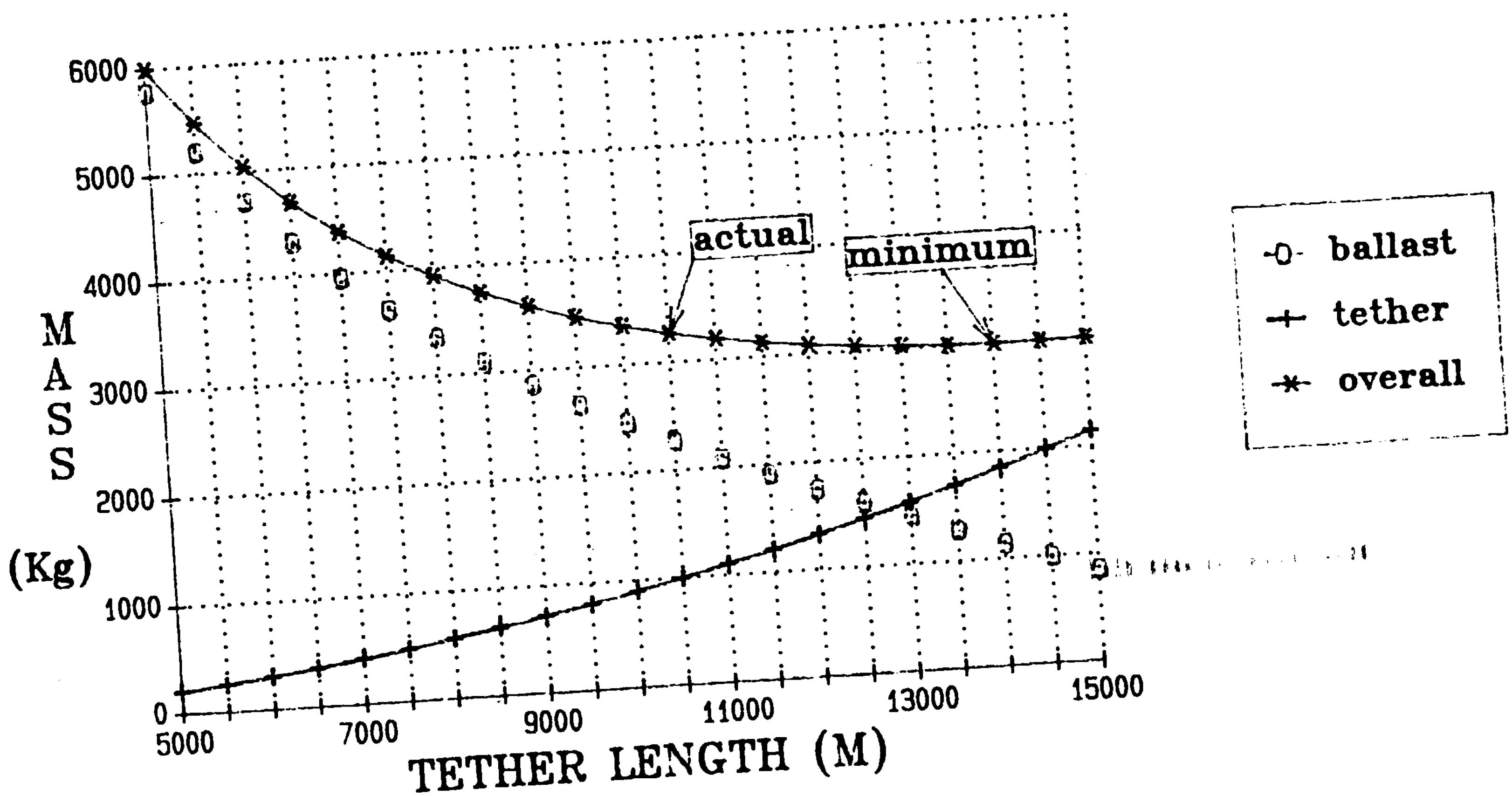
- o VGL AS DUAL CAPABILITY FACILITY (VARIAB. GRAVITY/GOOD MICRO-G QUALITY)
- o DISCRETE G-LEVELS IN THE RANGE 10-6 TO 10-2 G
- o PHASE-1 SPACE STATION SCENARIO
- o SINGLE TIME-SHARING VGL TETHER SYSTEM SELECTED
    - DEPLOYMENT FOR A LIMITED TIME (OPERAT. CONSTRAINTS LIMITATION)
    - VGL HAS TO BE CONSIDERED THE MICRO-G EXPERIMENT AT THAT TIME
- o ELEVATOR VGL SYSTEM SELECTED
    - SCIENTIFIC REQUIREMENTS SATISFIED
    - EFFICIENT EXPLOITATION OF TETHER CAPABILITIES

VGL SYSTEM ANALYSIS

ELEVATOR SIZING

- o ASSUMPTIONS
  - ELEVATOR MASS= 2000 KG
  - MINIMUM DISTANCE BETWEEN ELEVATOR AND SPACE STATION = 140 M
  - TETHER ABLE TO STAND METEORITIC DAMAGE (95% PROBABILITY FOR FOUR MONTHS)
- o RESULTS
  - MINIMUM VGL SYSTEM MASS FOR TETHER LENGTH = 14000 M
  - SLIGHTLY HEAVIER (10%) BUT MUCH SHORTER (33%) CONFIGURATION SELECTED
  - TETHER LENGTH = 10500 M
  - TETHER DIAMETER = 0.009 M
  - BALLAST MASS = 2200 KG
  - MAX ACHIEVABLE GRAVITY LEVEL ON THE VGL = $0.4*10^{-2}$ G

VGL SYSTEM MASS VS. TETHER LENGTH



VGL SYSTEM ANALYSIS

VARIABLE TETHER LENGTH

- o STATEMENT OF THE PROBLEM

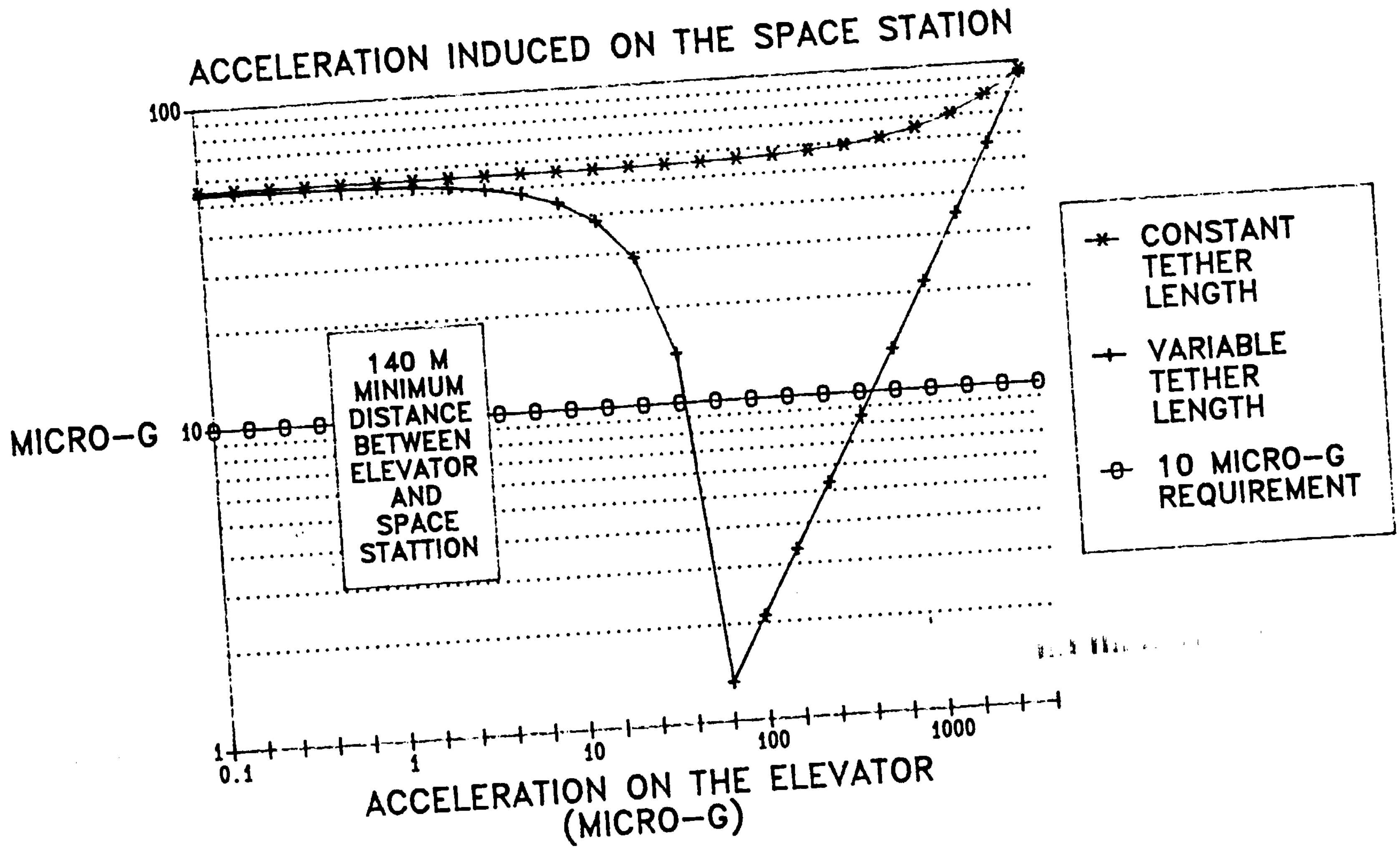
  IS IT WORTHWHILE TO CHANGE TETHER LENGTH DURING A MISSION?

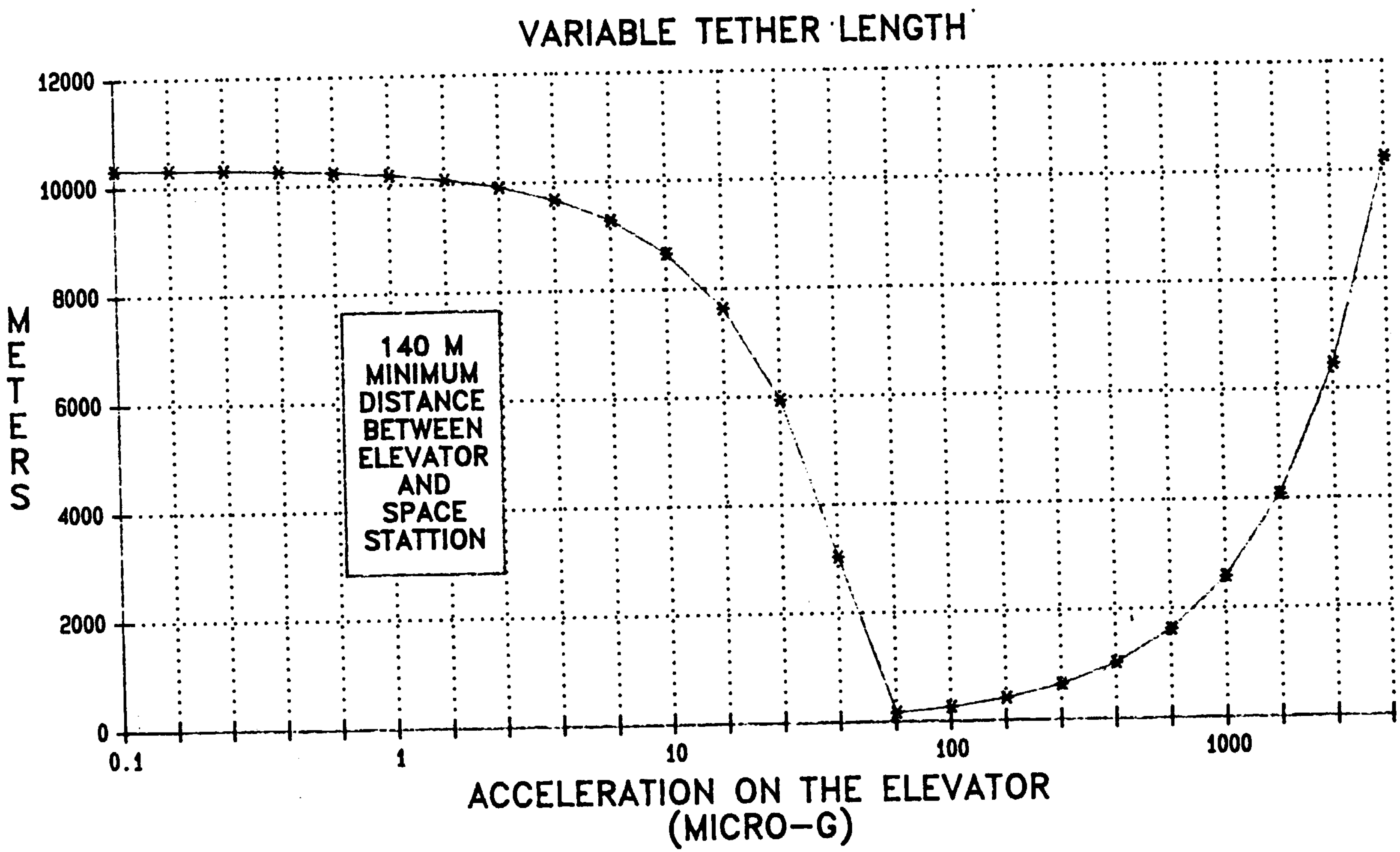
- o PURPOSES:
  - REDUCE ACCELERATION LEVEL ON SPACE STATION DURING ELEVATOR MISSION
  - REDUCE TETHER EXPOSURE TO METEORITIC DAMAGE

- o RESULTS
  - ACCELERATION LEVEL ON SPACE STATION SIGNIFICANTLY REDUCED ONLY FOR A LIMITED RANGE OF ELEVATOR POSITION
  - LARGE TETHER LENGTH CHANGE REQUIRED CAUSING OPERATIONAL PROBLEM

- o CONCLUSION
  - TETHER LENGTH WILL BE KEPT FIXED DURING ELEVATOR MISSION

VGL SYSTEM ANALYSIS




VARIABLE TETHER LENGTH
12000
10000
8000
6000
4000
2000
0
METERS
140 M
MINIMUM
DISTANCE
BETWEEN
ELEVATOR
AND
SPACE
STATTION
0.1
1
10
100
1000
ACCELERATION ON THE ELEVATOR
(MICRO-G)

VGL SYSTEM ANALYSIS

ANALYSIS FOCAL POINTS

o "CONVENTIONAL" SUBSYSTEMS

- POWER IS CRITICAL AS LONG AS SOLAR ARRAYS USE IS LIMITED
- THERMAL CONTROL SUBSYSTEM IS CONDITIONED BY SURFACE AREA AVAILABLE

o VGL PECULIAR PROBLEMS

- TETHER GOING THROUGH THE ELEVATOR?
- ELEVATOR/TETHER MECHANICAL INTERFACE (TETHER GRAPPLING, ELEVATOR BRAKING, TETHER DISENGAGEMENT,ETC...)
- ELEVATOR MOTION ACTUATORS AND ACCELERATION SENSORS

o SPACE STATION SEGMENT

- DOCKING SYSTEM
- TETHER DEPLOYER
- OPERATIONAL PROBLEMS

TETHER DEPLOYER

DEPLOYER SIZING

- o DEPLOYER FUNCTIONS
  - TETHER STORAGE DURING NON - OPERATIVE PHASE
  - TETHER DEPLOYMENT AND RETRIEVAL
- o GENERAL CONFIGURATION
  - A LARGE DRUM WITH THE SYMMETRY AXIS ALIGNED WITH THE Y AXIS (NO CONSTRAINT ON DRUM LENGTH)
- o POSITION
  - TETHER ATTACHMENT POINT ON LOCAL VERTICAL THROUGH THE SPACE STATION CENTER OF MASS
  - DEPLOYER WILL BE PLACED ON THE SKY LOOKING SIDE OF THE TRANSVERSAL BOOM
  - TETHER DEPLOYED OPPOSITE TO THE EARTH

TETHER DEPLOYER

DEPLOYER SIZING

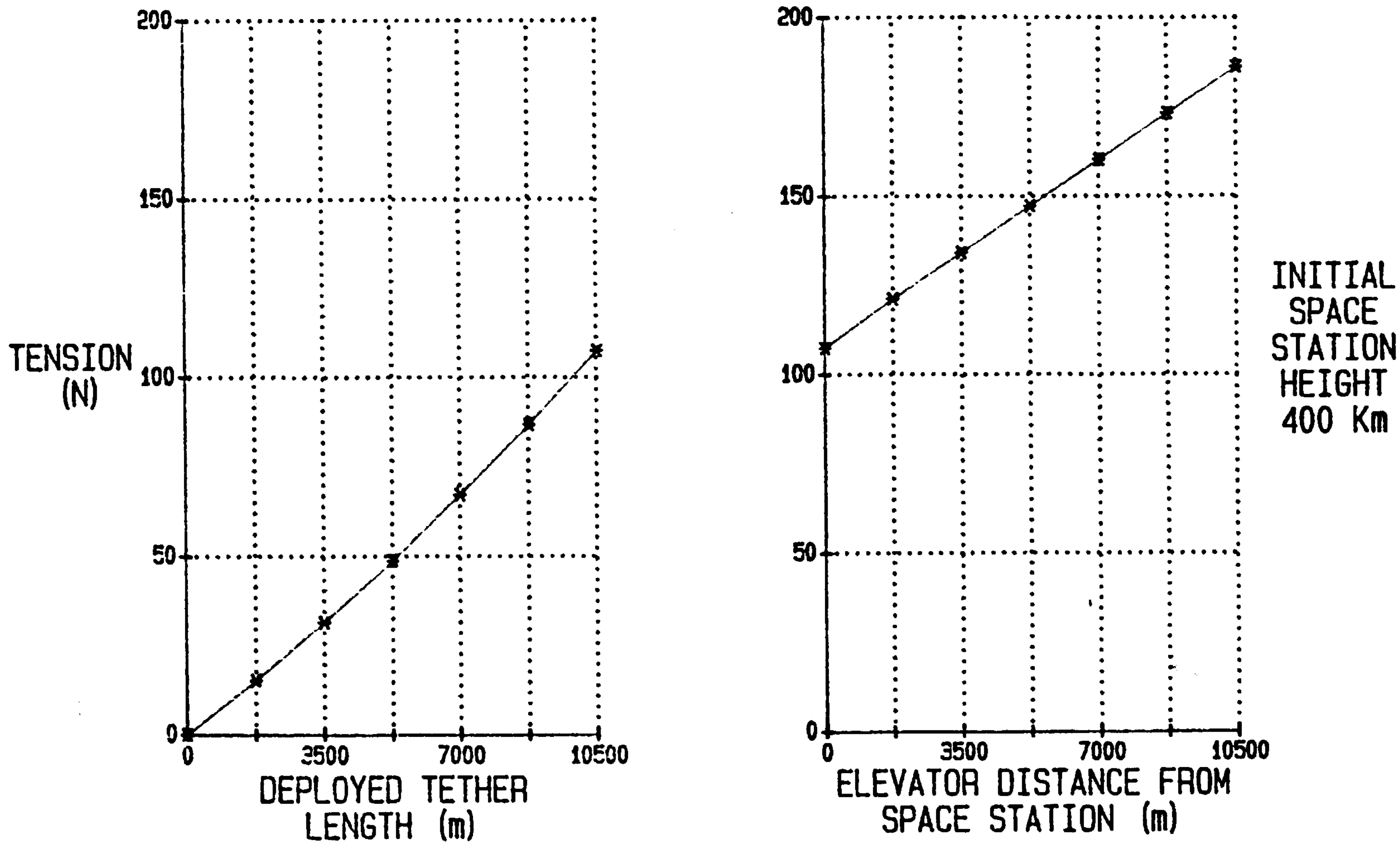
o ASSUMPTIONS

- MAX STRESS ON THE TETHER FABRIC = $2*10^8$ N/M^2
- TETHER WINDED AROUND THE DRUM IN TWO 'ROWS'

o RESULTS

- DEPLOYER DRUM DIAMETER = 3.6 M
- NEARLY 1000 DRUM TURNS REQUIRED FOR TETHER RETRIEVAL
- MAX EMERGENCY TORQUE = 300 N*M (ELEVATOR JAMMED ON THE TETHER) SIZING CONDITION FOR THE ELECTRICAL DRIVE MOTOR
- MAX NOMINAL RETRIEVAL TORQUE = 180 N*M
- MAX TORQUE REQUIRED FOR TETHER FLEXING = 39 N*M
- MAX TENSION DUE TO TETHER AND BALLAST (ONLY) = 107 N
- MAX TETHER TENSION = 180 N

TETHER DEPLOYER



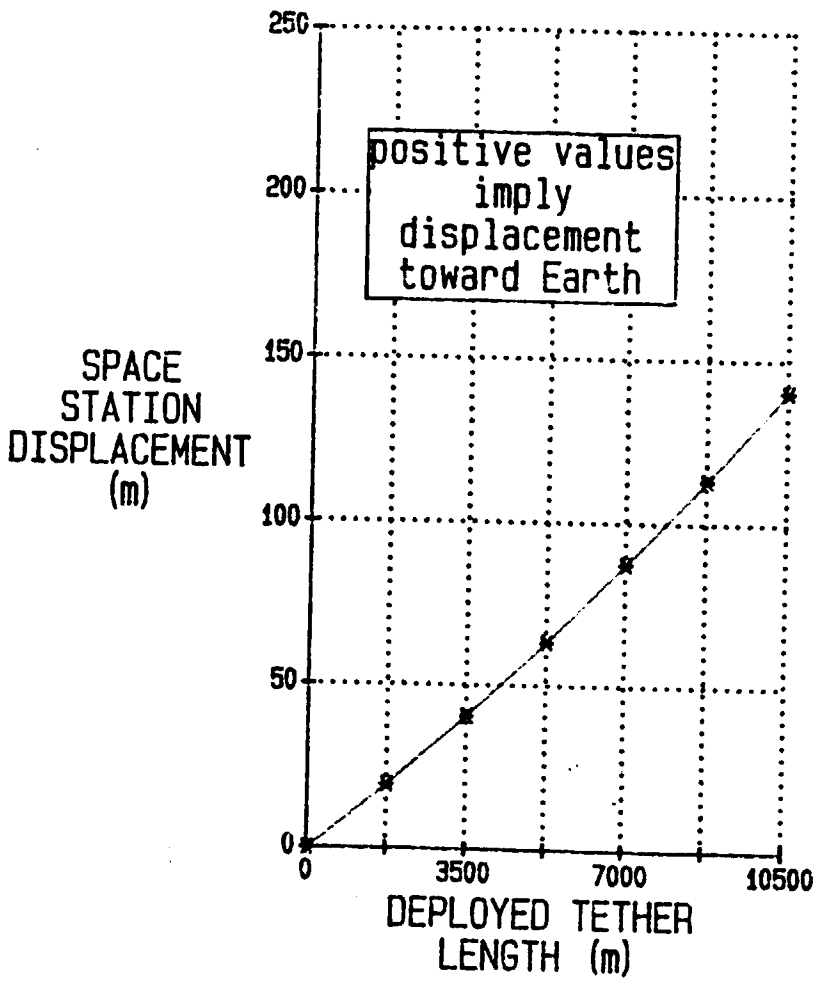
TETHER DEPLOYER

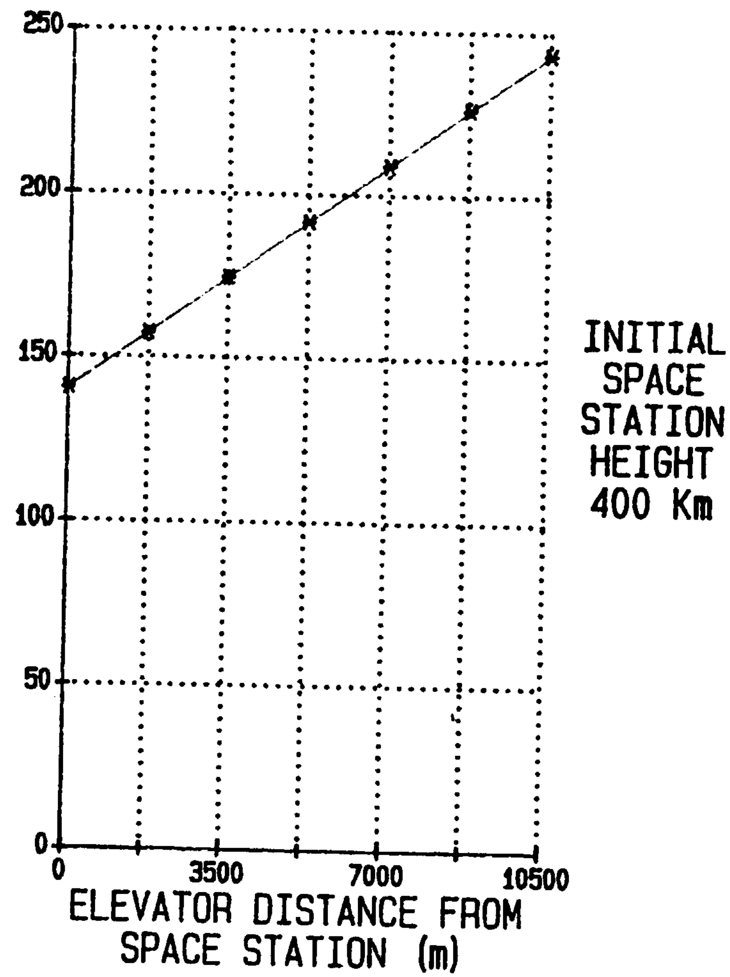
DEPLOYMENT SIDE EFFECTS

- o DEPLOYER/SPACE STATION SIDE EFFECTS
  - SPACE STATION HEIGHT CHANGED BY 250 M AT MAX
  - ORBITAL SPEED CHANGES BY 0.25 M/S AT MAX

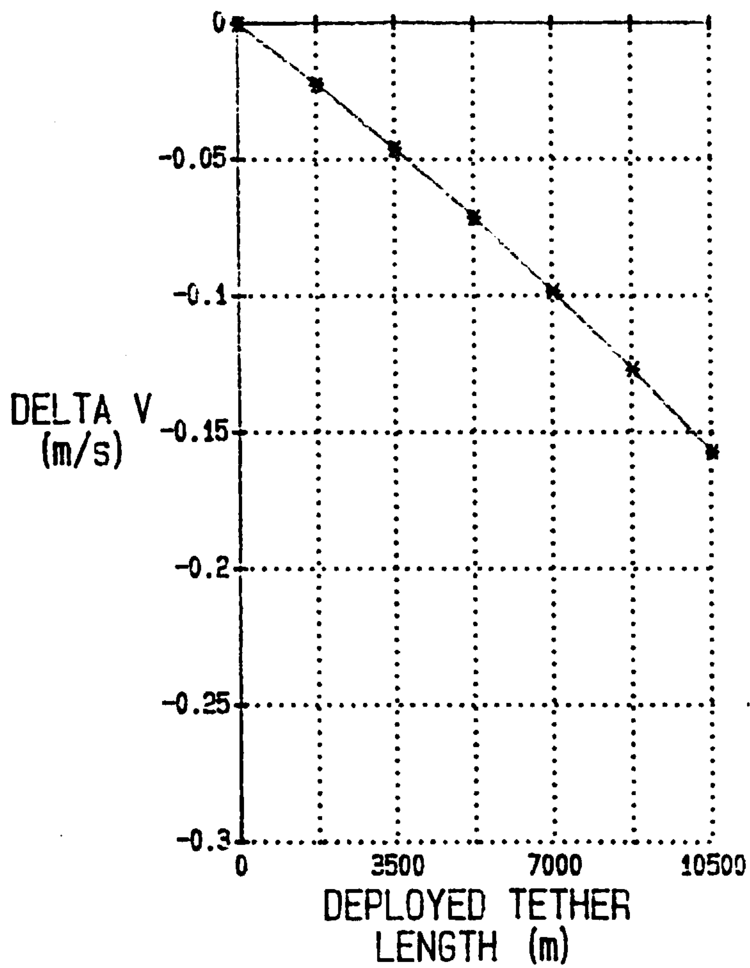
- o CONCLUSIONS
  - DRUM SIZE ACCEPTABLE
  - LOW TORQUE REQUIRED FOR TETHER RETRIEVAL
  - SMALL SIDE EFFECTS DUE TO TETHER DEPLOYMENT

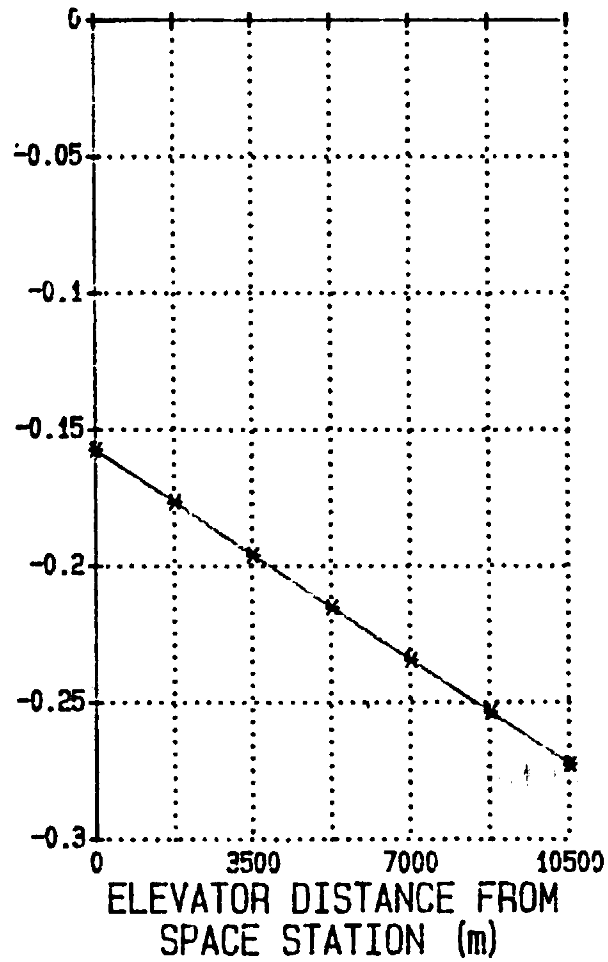
TETHER DEPLOYER





TETHER DEPLOYER

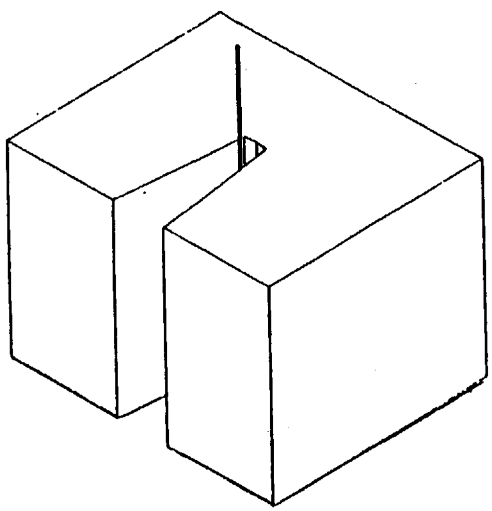




INITIAL
SPACE
STATION
HEIGHT
400 Km

VGL/TETHER CONFIGURATION

'SLOT' CONFIGURATION



SLOT PERMITS VGL/TETHER MATING MOVING ONLY THE ELEVATOR

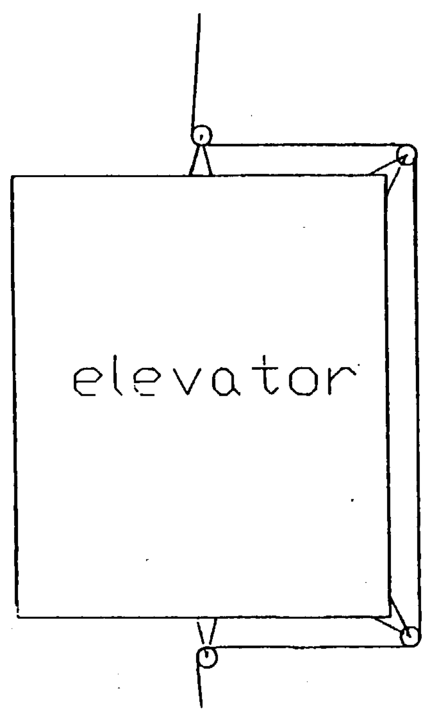
VGL/TETHER MATING DECOUPLED FROM TETHER OPERATIONS (DEPLOYMENT/RETRIEVAL)

IMPACT ON VGL CONFIGURATION NOT NEGLIGIBLE

CARE REQUIRED TO MATE TETHER AND ELEVATOR

VGL/TETHER CONFIGURATION

SHAPED TETHER CONFIGURATION



TETHER GOES AROUND THE VGL

SIMPLIFICATION IN VGL DESIGN

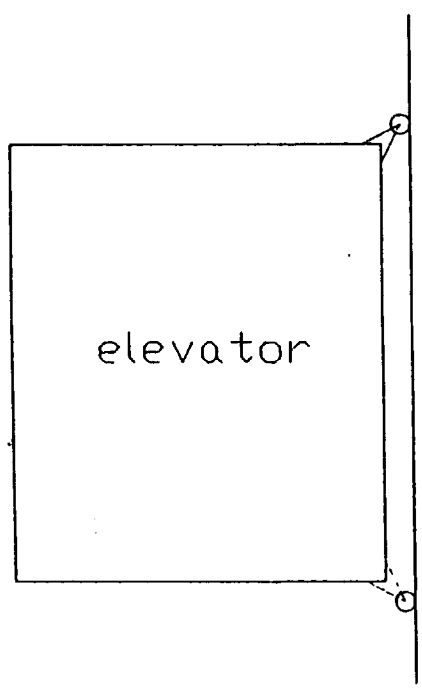
LARGE STRESSES IN THE TETHER

IF TETHER IS IN TENSION THE MATING IS OF DOUBTFUL FEASIBILITY;
TO ELIMINATE TETHER TENSION BALLAST MUST BE RETRIEVED

DURING ELEVATOR MOTION A DISPLACEMENT WAVE IS SUPERIMPOSED TO TETHER NATURAL DEFORMATION SHAPE

VGL/TETHER CONFIGURATION

UNBALANCED CONFIGURATION



VGL 'APPENDED' FROM ONE SIDE ON THE TETHER

SIMPLIFICATION IN VGL DESIGN AND TETHER MATING FASTEN

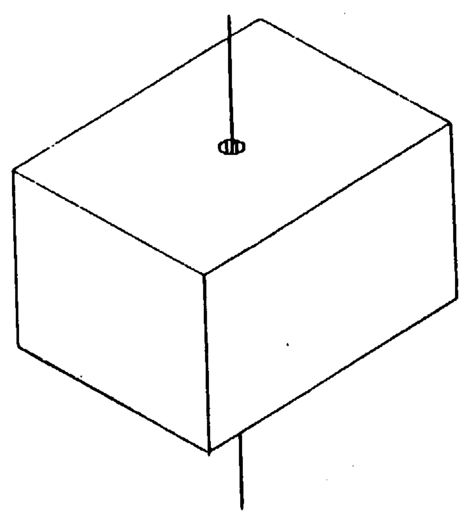
LARGE STATIC EQUILIBRIUM ANGLES (SEE CHARTS)

REQUIREMENT TO KEEP C.O.M. NEAR TETHER NOT EASILY MET

STRESSES IN THE TETHER CAN BE LARGE

VGL/TETHER CONFIGURATION

'HOLE' CONFIGURATION



TETHER IS INTRODUCED WITHIN THE HOLE USING A RIGID GUIDE

COMPARED WITH THE 'SLOT' CONFIGURATION:
- SIMPLER ELEVATOR CONFIGURATION
- HIGHER STRUCTURAL STIFFNESS
- LESS EMPTY ROOM

ELEVATOR CAN BE DISENGAGED FROM TETHER ONLY AFTER RETRIEVAL (OR TETHER CUT)

VGL OPERATION

RETRIEVAL - NOMINAL CONDITION

LOT' ELEVATOR		'HOLE' ELEVATOR
MOVE ELEVATOR (NEAR STATION)-	1)	MOVE ELEVATOR (NEAR BALLAST) DURING TETHER OPERATIONS TETHER SHOULD NOT GO THROUGH THE ELEVATOR TO AVOID UNCERTAINTIES IN TETHER TENSION AND/OR TETHER RUBBING
DISCONNECT ELEVATOR	2)	RETRIEVE TETHER
RETRIEVE TETHER	3)	DISCONNECT BALLAST
	4)	DISCONNECT ELEVATOR

I NOMINAL CONDITION THE 'HOLE' ELEVATOR IS MORE EXPOSED TO THE RISKS INVOLVED IN TETHER PERATION (IT STAYS MORE TIME ON THE TETHER)

VGL OPERATION

RETRIEVAL - TETHER REEL JAMMING

.OT' ELEVATOR	'HOLE' ELEVATOR
MOVE ELEVATOR (NEAR STATION)	1) MOVE ELEVATOR (NEAR STATION)
DISCONNECT ELEVATOR	2) REPAIR TETHER REEL OR CUT TETHER
REPAIR TETHER REEL OR CUT TETHER	3) RETRIEVE TETHER
RETRIEVE TETHER	4) DISCONNECT BALLAST
	5) DISCONNECT ELEVATOR

THE WORST CASE IT IS POSSIBLE TO LOSE A PORTION OF THE TETHER AND THE BALLAST IN BOTH ONFIGURATIONS.

OTICE THAT THE OPERATION SEQUENCE FOR THE 'HOLE' ELEVATOR SIGNIFICANTLY DEPARTS FROM THE OMINAL ONE INCREASING RISKS

VGL OPERATION

RETRIEVAL - ELEVATOR JAMMING

'LOT' ELEVATOR	'HOLE' ELEVATOR	
RETRIEVE TETHER (UP TO ELEVATOR)	1) RETRIEVE TETHER	
DISCONNECT ELEVATOR	2) CLEAR TETHER PATH	OR CUT TETHER
COMPLETE TETHER RETRIEVAL	3) COMPLETE TETHER RETRIEVAL (TETHER GOING THROUGH THE ELEVATOR)	
	4) DISCONNECT BALLAST	
	5) DISCONNECT ELEVATOR	

IE IMPORTANT POINT HERE IS THE FACT THAT IN THE 'HOLE' ELEVATOR YOU ARE NOT THROUGH EVEN IF
OU ARE ABLE TO CLEAR THE TETHER PATH.

IE RETRIEVAL AFTER THE REPAIR IS DIFFERENT FROM NOMINAL IN THAT THE TETHER GOES THROUGH THE
LEVATOR.

VGL/TETHER CONFIGURATION

CONCLUSIONS AND CONFIGURATION SELECTION

IBALANCED VGL DESIGN SHOWS UNACCEPTABLE BEHAVIOUR IF RELATIVELY HIGH G MISSION ARE FORE-
EEN

'SHAPED TETHER' VGL DESIGN TETHER INSERTION IMPLIES DIFFICULT PROBLEM

OLE' ELEVATOR CONFIGURATION COMPARES FAVOURABLY WITH THE 'SLOT' ONE

LOT' ELEVATOR OPERATIONS MORE STREAMLINED AND SAFE THAN THE 'HOLE' ONES

ETTER ACCESS/VISIBILITY TO THE TETHER PATH AND MECHANISMS OFFERED BY THE SLOT

VGL/TETHER CONFIGURATION

CONCLUSIONS AND CONFIGURATION SELECTION

LOT' ELEVATOR <u>OPERATIONAL SIMPLICITY PREFERRED</u> TO 'HOLE' ELEVATOR CONFIGURATION ADVANTAGE

'HOLE' ELEVATOR OPERATIONS IN CASE OF MALFUNCTIONING APPEAR RISKY
IN CONFIGURATION WHICH REQUIRE TO UNFASTEN VGL DO NOT REQUIRE TETHER OPERATIONS

LOT' ELEVATOR OFFERS MORE POTENTIAL FOR LONG DURATION / SEMIPERMANENT TETHERED FACILITIES EVELOPMENT

OTHER USES OF THE ELEVATOR (DIFFERENT FROM VGL) ARE POSSIBLE AS ARE OTHER SPACE STATION/TETHER(S) CONFIGURATION

<u>'SLOT' ELEVATOR IS THE BASELINE CHOICE</u>

ALONG TETHER MOTION

ACTUATOR CHOICE

HREE POSSIBILITIES:

JETS PROPULSION

STANDARD WAY OF MOVING THINGS IN SPACE
HUNDREDS OF KGS OF COLD GASES REQUIRED (VERY SLOW MANOEUVRES FOR QUITE LONG TIMES)
HYDRAZINE IS AN HAZARD WHEN FIRING TOWARD SPACE STATION OR NEAR TETHER
JET FINITE RESOLUTION CAN HARDLY ASSURE THE REQUIRED PRECISION IN ELEVATOR POSITIONING

) ELECTROMAGNETIC PROPULSION

CONCEPTUAL POSSIBILITY
REQUIRE AN 'AD HOC' TETHER POSSIBLY WITH PERMANENT MAGNETS
TETHER COST (DEVELOPMENT AND MANUFACTURING) LIKELY TO BE HIGH
INCREASED DEPENDENCE AND INTERACTION WITH SPACE STATION

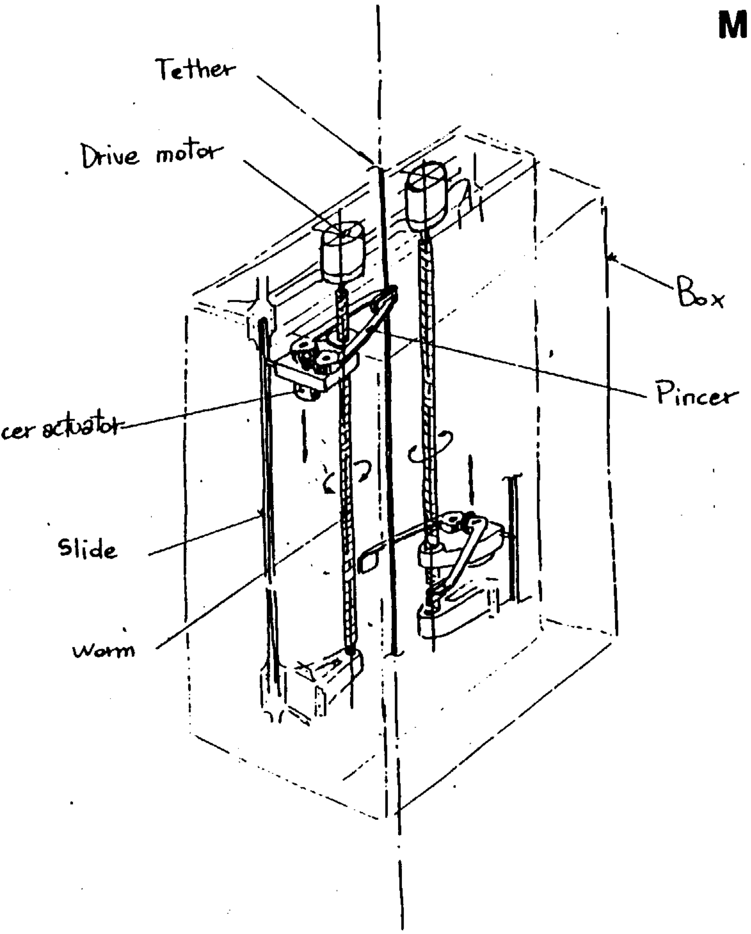
) MECHANISM

EXPLOIT FRICTION ON PHYSICAL CONTACT BETWEEN TETHER AND ELEVATOR
LONG DURATION STATION KEEPING CAN BE ACCOMPLISHED WITH NO ENERGY EXPENDITURE (BRAKES)
TETHER KEPT NATURALLY APART FROM SLOT WALLS
PROPER MATERIALS CAN MINIMISE TETHER AND MECHANISM WEAR

MECHANISM CONCEPT SELECTED

ALONG TETHER MOTION

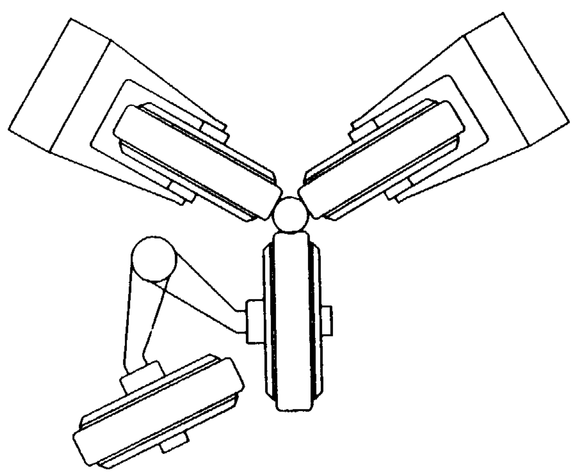
MECHANISM SELECTION



- ROBOTIC CONCEPT
- PINCERS GRASP TETHER ALTERNATIVELY DURING STROKE
- VERY PRECISE POSITIONING
- SYNCHRONIZATION REQUIRES COMPLEX CONTROL SYSTEM
- STRONG PERIODIC EXCITATION DUE TO TETHER TENSION CHANGES

ALONG TETHER MOTION

MECHANISM SELECTION



WHEELS CONCEPT

TWO SETS OF THREE WHEELS (SPRING MOUNTED)

WHEEL PRESSURE ON THE TETHER IS REGULATED TO GENERATE PROPER FRICTION FORCES

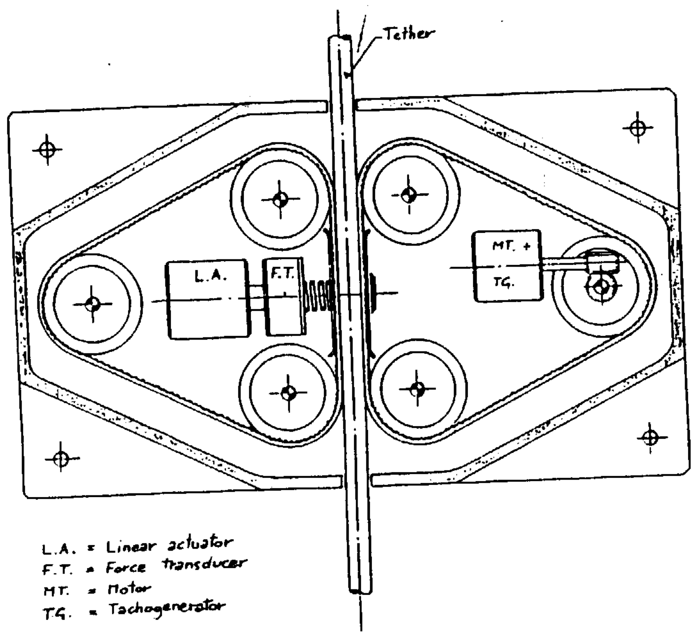
SIMPLE CONTROL SYSTEM

EASY ACCESS AND VISIBILITY

SMALL CONTACT AREA REQUIRES CAREFUL SURFACE PROPERTIES SELECTION TO AVOID WEAR

ALONG TETHER MOTION

MECHANISM SELECTION



COG BELTS CONCEPT

TWO SETS OF COG BELTS

ENLARGED CONTACT AREA REDUCE WEAR

SIMPLE CONTROL SYSTEM

REDUCED ACCESS AND VISIBILITY

HARDWARE COMPLEXITY AND RELIABILITY ARE A CONCERN

ALONG TETHER MOTION

MECHANISM SELECTION

<u>THE BASELINE ACTUATORS FOR ELEVATOR MOTION ALONG TETHER ARE THE WHEELS</u>

MPLICITY OF CONCEPT AND OF HARDWARE IMPLEMENTATION THE MAIN ADVANTAGES

ATURAL' TETHER MATING

TETHER WEAR DUE TO WHEELS NOT ACCEPTABLE THE COG BELTS ARE THE BACK UP SOLUTION

OBOTIC CONCEPT TOO COMPLEX AND 'NOISY' TO BE ACCEPTABLE

CONFIGURATION CONSTRAINTS

EVATOR CONFIGURATION IS CONSTRAINED BY SYSTEM REQUIREMENTS

LEVEL: THE VGL CAPABILITY TO PERFORM ITS MISSION DEPENDS ON:

SUBSYSTEM ABILITY TO WORK IN CONDITION WHICH CAN BE QUITE DIFFERENT FROM ZERO G. MECHANISMS AND SOME COMPONENTS SUCH AS HEAT PIPES MUST BE ANALYZED UNDER THIS RESPECT

NEAR ZERO G
VERY LOW ACCELERATION VALUES DEMAND LOW MECHANICAL NOISE FROM SUBSYSTEMS AND LOW STRUCTURAL DISTURBANGE PROPAGATION

CCESS: BY DESIGN VGL IS A REPAIRABLE, REFURBISHABLE SYSTEM.

EASY ACCESS TO MOST SUBSYSTEMS AND EQUIPMENTS IS PREREQUISITE
EASY ACCESS TO EPDS IS NEEDED TO REPLACE BATTERIES
CRITICAL MECHANISMS VISUAL INSPECTION IS REQUIRED

CONFIGURATION CONSTRAINTS

CONT'D

AYLOAD REPLACEMENT: BY DESIGN VGL IS ABLE TO ACCOMMODATE DIFFERENT PAYLOADS IN DIFFERENT ISSIONS

- MECHANICAL INTERFACES AND "OPEN" STRUCTURE MUST BE PROVIDED
- THERMAL, EPDS AND ELECTRONICS "USER FRIENDLY" INTERFACES

- ACS INFLUENCES AND IS INFLUENCED BY THE POSSIBLE MASS PROPERTIES OF THE PAYLOAD

LOT: THE PRESENCE OF THE SLOT DRIVES

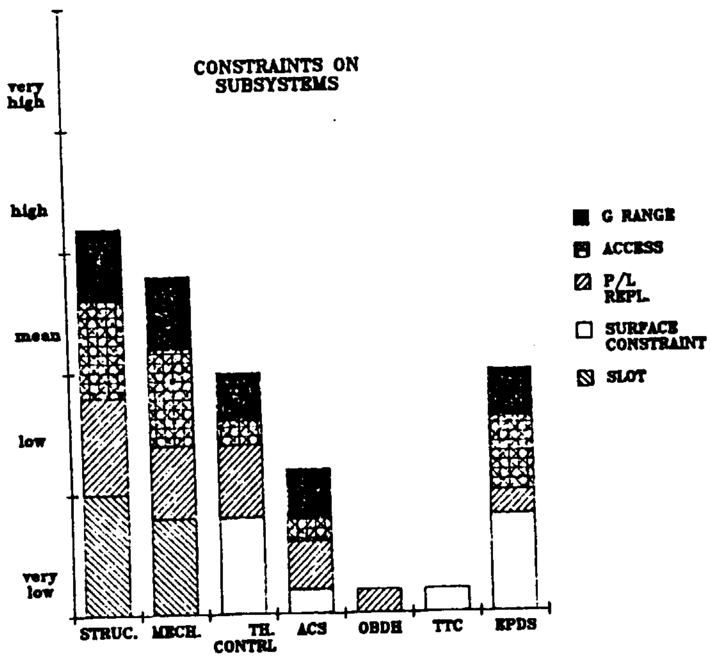
- OVERALL STRUCTURE SHAPE
- TETHER CONNECTING MECHANISM

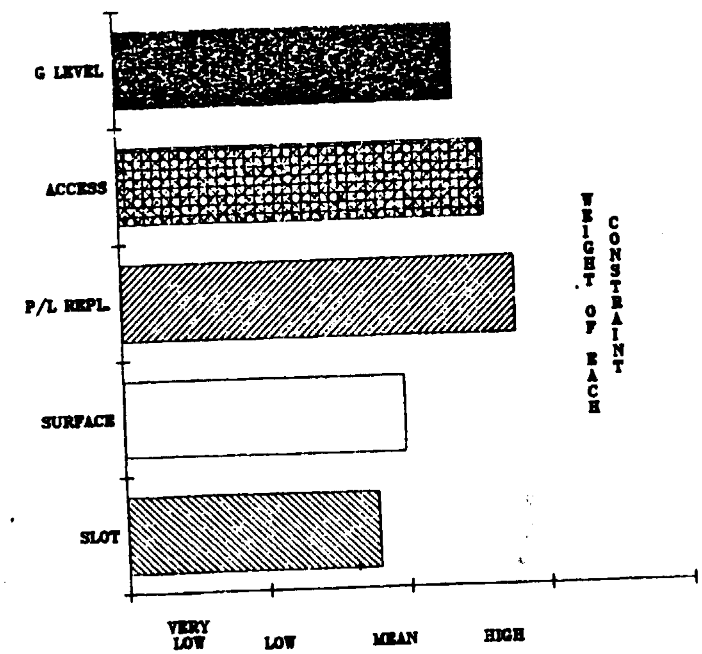
URFACE: ONLY A LIMITED SURFACE IS AVAILABLE FOR

- SOLAR ARRAYS
- THERMAL RADIATORS

CONFIGURATION CONSTRAINTS

PICTORIAL SUMMARY





THE MOST SEVERE CONSTRAINT IS DUE TO THE CAPABILITY OF PAYLOAD REPLACEMENT

ORIGINAL PAGE IS OF POOR QUALITY

PAYLOAD CONFIGURATION

PAYLOAD LOCATION

YLOAD MUST LIE NEAREST POSSIBLE TO THE TETHER IN THE PLANE PERPENDICULAR TO IT

S IS SO TO REDUCE GRAVITY GRADIENT AND ATTITUDE MOTION UNWANTED RESIDUAL ACCELERATIONS.

THE DIRECTION ALONG THE TETHER THE PAYLOAD CENTER OF MASS (C.O.M.) SHOULD BE COINCIDENT
TH THE VGL C.O.M.

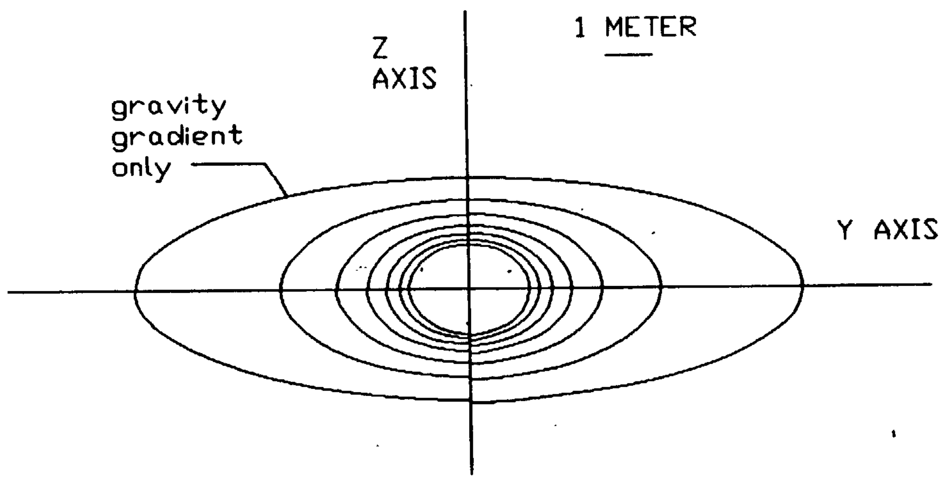
THIS WAY IT WILL BE POSSIBLE TO REDUCE UNCERTAINTIES IN POSITION OF THE PAYLOAD AND PROB-
MS WHICH COULD RISE WHEN ADAPTING THE ELEVATOR TO PAYLOADS OF DIFFERENT MASSES

PAYLOAD CONFIGURATION

PAYLOAD SIZE

THE MOST DEMANDING CONDITION FOR THE ELEVATOR IS THE 1 MICROG G ACCELERATION LIMIT. THE GRAVITY GRADIENT ALONE RESTRICT THE VOLUME IN WHICH THIS CONDITION CAN BE MET TO A CYLINDER WITH AXIS ALONG THE ORBITAL PATH; ELLIPTICAL SECTION 5 M WIDE ALONG THE TETHER; 15 M IN THE OUT OF PLANE DIRECTION

DRAG AND ATTITUDE MOTION ACCELERATION RESTRICT THESE DIMENSIONS



SENSIBLE VALUES FOR THE PAYLOAD SIZE ARE

X=2 M	Y=1.8 M	Z=1.5 M
ALONG FLIGHT DIRECTION	ALONG OUT OF PLAN DIRECTION	ALONG TETHER DIRECTION

PAYLOAD CONFIGURATION

PAYLOAD SIZE

/O BASIC PAYLOAD CONFIGURATION SOLUTIONS:

YLOAD RACKS

- SET OF RACKS ON THE VGL, EACH ABLE TO HOUSE ONE PAYLOAD
- SIMPLE FOR THE EXPERIMENTER, VERY BURDENSOME FOR THE VGL (MANY MULTIPLE INTERFACES ARE REQUIRED)
- ATTEMPT TO SATISFY ALL POSSIBLE REQUIREMENTS WOULD LEAD TO OVERDESIGN

YLOAD MODULE

- ONE PAYLOAD MODULE, SEPARABLE FROM VGL ITSELF
- ONLY ONE SET OF INTERFACES IS REQUIRED
- MAJOR PAYLOAD REPLACEMENT/REPAIR/RESUPPLY WOULD REQUIRE COMPARATIVELY SHORT TIMES

THE NEED ARISES THE PAYLOAD MODULE CAN HOUSE A SET OF RACKS AS A COMPROMISE SOLUTION

PAYLOAD MODULE BASELINE SOLUTION

THERMAL CONTROL ISSUES

'ZERO' ORDER ANALYSIS (PASSIVE THERMAL CONTROL)

SSUMPTIONS

SURFACE AREA DISTRIBUTION APPROXIMATED BY A 1.5 M HIGH AND 1.5 M WIDE CYLINDER

PAYLOAD/SERVICES HEAT LOAD FROM 100 TO 400 W
HEATERS POWER UP TO 200 W

TEMPERATURE RANGE FROM 258 TO 313 K

COLDEST CASE: VGL IN FULL SHADOW
HOTTEST CASE: ORBITAL NOON

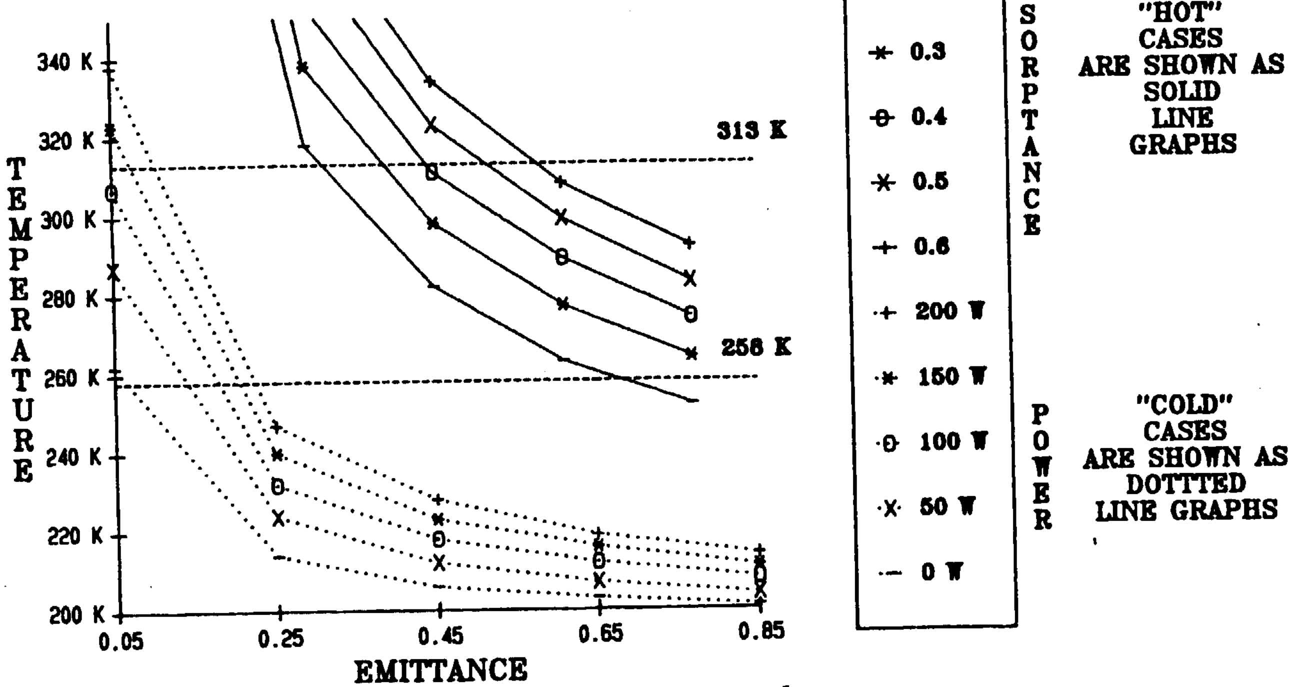
WIDE RANGE OF ABSORPTANCE, EMITTANCE (ASSUMED CONSTANTS THROUGHOUT THE SURFACE)
AND HEATERS POWER SWEPT

THERMAL CONTROL ISSUES

'ZERO' ORDER ANALYSIS (PASSIVE THERMAL CONTROL) - CONT'D

ESULTS

VGL TEMPERATURES IN "COLD" AND "HOT" CASES AS A FUNCTION OF POWER AND ABSORPTANCE



NO SET OF ABSORPTANCE, EMITTANCE AND POWER MEETS THE REQUIREMENT

THERMAL CONTROL ISSUES

THERMAL CONTROL OPTIONS

SSIVE SYSTEM

- EXPLOIT COMBINATION OF SURFACE PROPERTIES AND HEATERS
- USUAL METHOD FOR THERMAL CONTROL
- DIFFICULT TO IMPLEMENT GIVEN PAYLOAD VARIABILITY

EMI-PASSIVE SYSTEM

- USE HEAT PIPES, LOUVERS AND SHUTTERS BUT NO FLUID LOOP
- ABLE TO DEAL WITH RELATIVELY LARGE CHANGE IN HEAT INPUT
- RELIABILITY IS A CONCERN

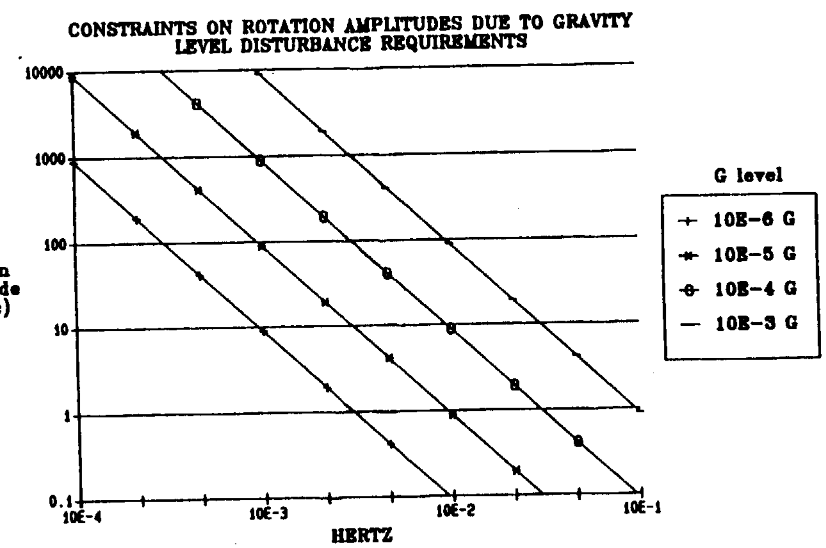
CTIVE SYSTEM

- FLUID LOOP SUPPLIED BY A PUMP
- LARGEST FLEXIBILITY IN DEALING WITH VARIABLE HEAT INPUTS
- PUMP CAUSES DISTURBANCES TO MICRO G ENVIRONMENT
- INTERFACING THE FLUID LOOP WITH PAYLOAD CAN BE A PROBLEM

<u>THE PREFERRED SOLUTION IS A SEMIPASSIVE SYSTEM</u>

ATTITUDE CONTROL SYSTEM

REQUIREMENTS



ACS REQUIREMENTS COME FROM

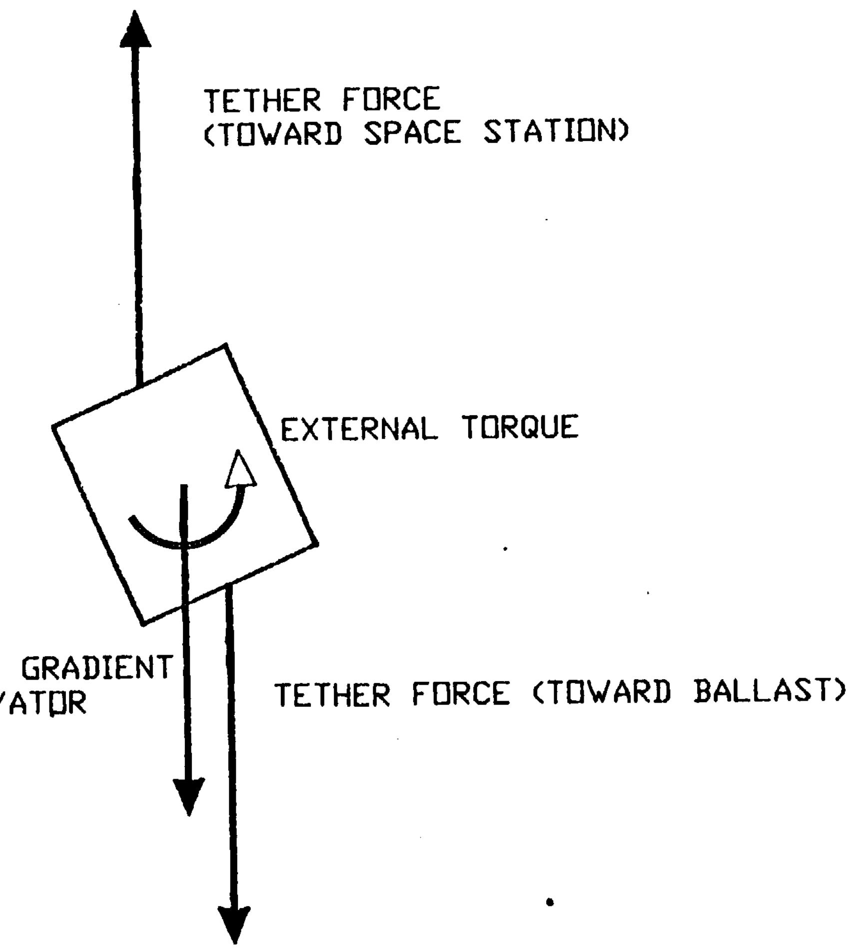
- SOLAR ARRAYS/RADIATORS POINTING ERROR: QUITE LARGE VALUES ACCEPTABLE (2-3 DEGREES)

- PAYLOAD ALLOWABLE ACCELERATION RESTRICTS POINTING STABILITY: ACCEPTABLE VALUES SHOWN IN THE CHART

RELATIVELY LARGE OSCILLATION ACCEPTABLE IF LOW FREQUENCIES ARE INVOLVED

ATTITUDE CONTROL SYSTEM

TETHER INDUCED TORQUES



WHEN THE ELEVATOR YAW AXIS IS NOT ALIGNED WITH THE TETHER TENSION CAUSES A RESTORING TORQUE ON IT AROUND PITCH AND ROLL AXIS

TORSIONAL STRUCTURAL TETHER STIFFNESS RESTRAINS YAW ELEVATOR MOTION

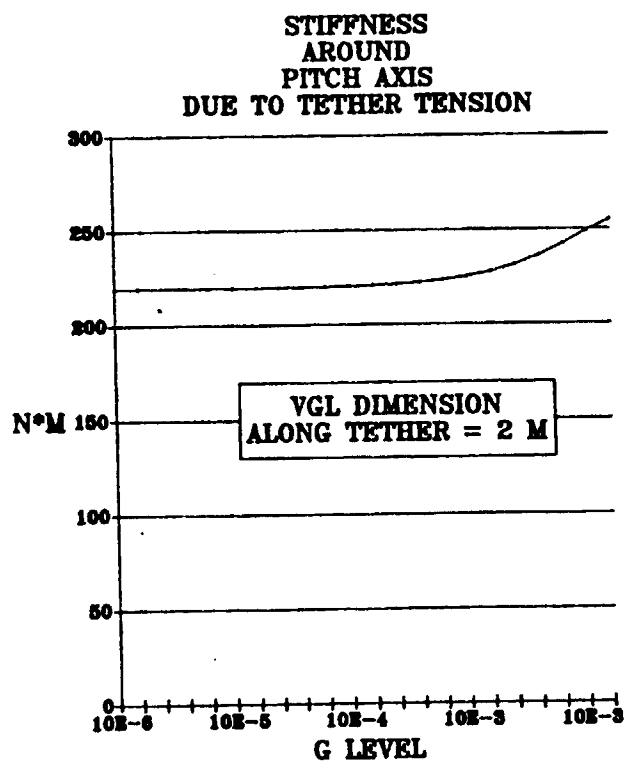
TETHER INDUCED 'STIFFNESS' AROUND PITCH AND ROLL APPROX EQUAL

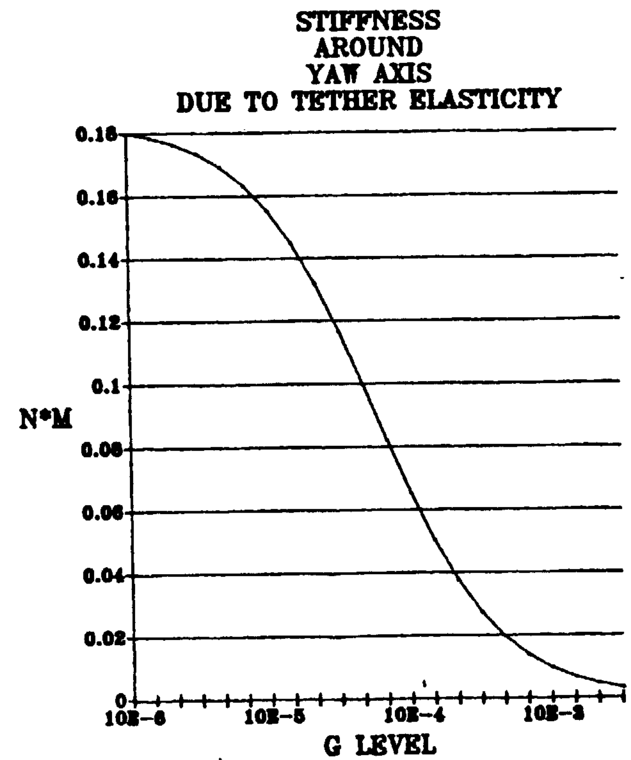
PITCH/ROLL 'STIFFNESS' INCREASES SLIGHTLY WITH DISTANCE FROM C.O.M.

TORSIONAL STIFFNESS DECREASES QUICKLY WITH DISTANCE

ATTITUDE CONTROL SYSTEM

TETHER INDUCED TORQUES-CONT'D





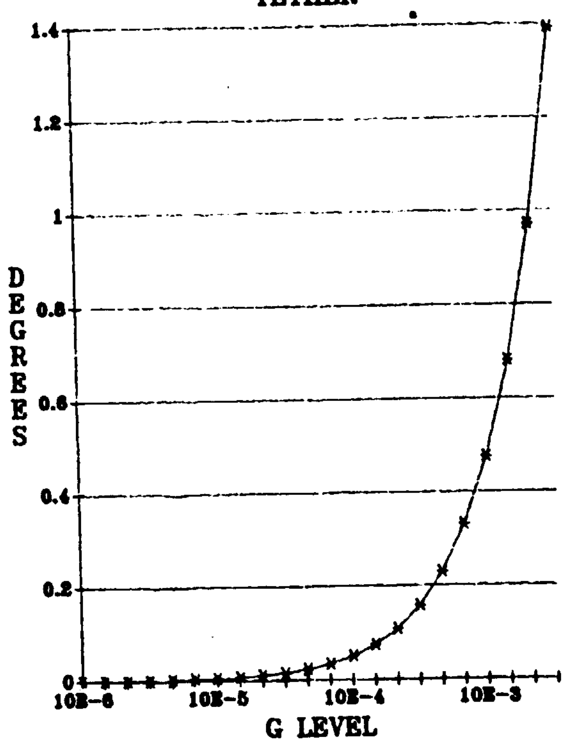
PITCH/ROLL STIFFNESS PRESUMABLY DOMINATE ALL OTHER EFFECTS

YAW MOTION CAN BE INFLUENCED BY TETHER TORSIONAL STIFFNESS

ATTITUDE CONTROL SYSTEM

ENVIRONMENTAL TORQUES

VGL MISPOINTING DUE TO A 0.1 M C.O.M. SHIFT FROM TETHER



ASSUMING REASONABLE SYMMETRY AND MASS BALANCE OF THE ELEVATOR AERODYNAMIC DRAG AND SOLAR PRESSURE TORQUES SHOULD BE NEGLIGIBLE

NO SIGNIFICANT MAGNETIC TORQUE EXPECTED

IF THE ELEVATOR C.O.M. IS SHIFTED FROM TETHER GRAVITY GRADIENT CAUSES ROTATIONS AROUND PITCH/ROLL AXIS

ELEVATOR MISALIGNMENT NOT NEGLIGIBLE AT HIGH G VALUE (AS SHOWN)

ATTITUDE CONTROL SYSTEM

ACS EQUIPMENTS

NSORS

- FOUR GYROS AS MAIN SENSORS
- STAR/SUN SENSORS UPDATE GYROS
- STAR SENSOR LOOKING ALONG OUT-OF-PLANE DIRECTION AND SUN (/STAR) SENSOR LOOKING ALONG FLIGHT DIRECTION (ALONG-TETHER DIRECTION POSSIBLY OCCULTED BY BALLAST)
- INFORMATION ON THE POSITION OF THE ELEVATOR W.R.T. SPACE STATION AND TETHER CAN BE USEFUL

CTUATORS

- AROUND PITCH/ROLL AXES TETHER TENSION SUFFICIENT TO STABILIZE ELEVATOR
- NUTATION DAMPERS CAN BE USED EFFECTIVELY TO REDUCE HIGH FREQUENCY MOTION
- YAW REACTION WHEEL PROBABLY NEEDED
- COLD GAS JETS DESATURATE YAW WHEEL AND USED IN SPECIAL SITUATION (END OF MOTION, DOCKING)

ATTITUDE CONTROL SYSTEM

SUMMARY

ACS REQUIREMENTS CAME MAINLY FROM THE ELEVATOR MICRO G REQUIREMENT

MAIN ACTING TORQUES COME FROM TETHER/ELEVATOR INTERACTION

ACS CONTROLLED BY GYROS UPDATED BY STAR/SUN SENSORS

TETHER RESTORING TORQUES (AND DAMPERS) CONTROL PITCH AND ROLL

YAW WHEEL DESATURATED BY COLD GAS JETS

SIMULATION RESULTS NEEDED FOR SOUND ACS ASSESSMENT

POWER SUBSYSTEM

GENERAL

- o REASONS TO ANALYZE POWER SUBSYSTEM
  - POWER SUBSYSTEM IS CRITICAL AS LONG AS WE NOT USE SOLAR ARRAYS IN AN EXTENSIVE WAY
  - POWER SUBSYSTEM IS A DESIGN DRIVER

- o POWER REQUIREMENTS
  - AVERAGE POWER IN THE RANGE 200 TO 700 WATTS
  - MISSION DURATION BETWEEN 7 TO 30 DAYS
  - PEAK POWER REQUESTS WILL BE DEALT WITH A PROPER POWER MANAGEMENT

- o REFURBISHMENT
  - IN LINE OF PRINCIPLE, ELEVATOR CAN BE REFURBISHED ON THE SPACE STATION DURING A MISSION
  - REFURBISHMENT WILL BE AVOIDED DURING STANDARD MISSION

POWER SUBSYSTEM

GENERAL (CONT'D)

- o POWER SUBSYSTEM SELECTION CRITERIA
  - MASS. POWER SUBSYSTEM MASS MUST BE LESS THAN 1/3 OF TOTAL MASS
  - SIZE.
  - CLEANNESS. LOWEST POSSIBLE DISTURBANCES ON PAYLOADS DUE TO POWER SUBSYSTEM
  - FLEXIBILITY. CAPABILITY TO ADAPT TO PAYLOADS AND MISSIONS CRUCIAL
  - SAFETY, COST, DEVELOPMENT RISK, ETC.. WILL BE ASSESSED BUT NOT PIVOTAL FOR SELECTION

POWER SUBSYSTEM

POWER SOURCES

- o POSSIBLE POWER SOURCES

- TRANSMISSION.

  POWER GENERATED ON SPACE STATION IS TRANSMITTED TO ELEVATOR

- GENERATION.

  POWER GENERATED ON BOARD (RTG, SOLAR ARRAYS).
  ENERGY ALMOST UNLIMITED, POWER LIMITED

- STORAGE.

  POWER STORED ON BOARD (FUEL CELLS, BATTERIES)
  ENERGY - CONSTRAINED SYSTEMS BUT LARGE POWER FLEXIBILITY

POWER SUBSYSTEM

POWER TRANSMISSION

- POSSIBLE ALTERNATIVES

  - RADIANT ENERGY (MICROWAVES) PRODUCED ON SPACE STATION IS RECEIVED ON ELEVATOR.
    LOW EFFICIENCY AND HIGH POLLUTION

  - ELECTRICAL CURRENT THROUGH TETHER TRANSFERRED BY MAGNETIC INDUCTION TO ELEVATOR.
    TECHNICALLY DIFFICULT, HIGH MAGNETIC FIELD INDUCED NEAR THE PAYLOAD

  - TETHER USED AS POWER LINE.
    ELECTRICAL INSULATION PROBLEMATIC IF ELEVATOR CAN BE IN ANY POSITION ALONG TETHER

  - SECONDARY CABLE CONNECTS SPACE STATION TO ELEVATOR.
    TETHER/SECONDARY CABLE CAN ENTANGLE DURING ELEVATOR MOTION
    LARGE ELECTRICAL LOSSES UNLESS HIGH VOLTAGE USED

POWER SUBSYSTEM

POWER TRANSMISSION (CONT'D)

- DURING MICRO-G MISSION SECONDARY CABLE/CONDUCTIVE TETHER FEASIBLE (LOW DISTANCE)
- DURING VARIABLE G MISSIONS NO POWER TRANSMISSION SOLUTION PROMISING

o CONCLUSION

- POWER TRANSMISSION NOT BASELINE CHOICE.

POWER SUBSYSTEM

POWER GENERATION

- o RADIOISOTOPE THERMAL GENERATOR (RTG)
- PLUTONIUM DECAY HEAT USED TO GENERATE ELECTRICAL CURRENT
- TYPICAL UNIT: GENERAL ELECTRIC GPHS

  MASS = 50 KG
  POWER OUTPUT = 250 - 290 W
  SIZE = 0.42 M DIAMETER, 1.13 M HEIGHT
  EFFICIENCY = 6.5% (APPROX 4.5 THERMAL KW)

- TWO UNITS REQUIRED BY ELEVATOR
- GOOD VOLUME AND MASS POWER DENSITY
- SHIELD MASS SUBSTANTIAL IF UNITS PLACED NEAR PAYLOAD
  DIFFICULT HANDLING AND SAFETY ISSUES
  UNACCEPTABLY LARGE THERMAL OUTPUT

POWER SUBSYSTEM

POWER GENERATION (CONT'D)

o SOLAR ARRAYS (AND RECHARGEABLE BATTERIES)

ASSUMPTIONS

- SOLAR ARRAY POWER DENSITY = 125 W/M^2 ; 25 W/KG
- RECHARGEABLE BATTERIES ENERGY DENSITY (USEFUL) = 40 W/KG
- EFFICIENCY SOLAR ARRAYS - BATTERIES - PAYLOAD CYCLE = 0.65

RESULTS

- OVERALL MASS NEAR 70 KG
- SOLAR ARRAYS AREA = 10 M^2 (TWO AXES STEERABLE)

o CONCLUSIONS

TO BE ACCEPTABLE SOLAR ARRAYS AND RTG REQUIRE BOOMS THAT WE WANT TO AVOID (STRUCTURAL FLEXIBILITY)

POWER SUBSYSTEM

ENERGY STORAGE

o BATTERIES

- LITHIUM / $SOCL_2$ NOT RECHARGEABLE BATTERIES
- ENERGY DENSITY 490 W/KG; 950 KW/M^3 FOR LARGE SYSTEMS ON EARTH APPLICATION
- USED IN SMALLER VERSION ON SPACE SHUTTLE
- 1000 KG MASS AND 0.5 M^3 IN WORST CASE
- QUITE RELIABLE AND "QUIET" SYSTEM
- BATTERIES MASS EXCEEDINGLY LARGE IF NOT SUPPLEMENTED BY OTHER POWER SOURCES

o FUEL CELLS

- OXYGEN - HYDROGEN CYCLE
- USED IN GEMINI, APOLLO, SHUTTLE PROGRAMS
- ENERGY CONVERSION EFFICIENCY BETWEEN 50 AND 70 %
- GAS STORAGE AT 300 BAR IN COMPOSITE TANKS

POWER SUBSYSTEM

FUEL STORAGE

o GAS STORAGE ALTERNATIVES

- METALLIC HYDRURES.
  DISCARDED FOR LOW HYDROGEN MASS DENSITY (MAX 3%)

- CRYOGENIC STORAGE.

  REQUIRES SMALL AMOUNT OF DAILY EVAPORATION.
  TWO DRAWBACKS:
  POLLUTION RISK

  MASS INCREASE (100 % FOR A 30 DAYS MISSION AND 4% DAILY LOSS)

- HIGH PRESSURE TANKS

  COMPOSITE TANKS OFFER BEST PERFORMANCE

  SELECTED SOLUTION

POWER SUBSYSTEM

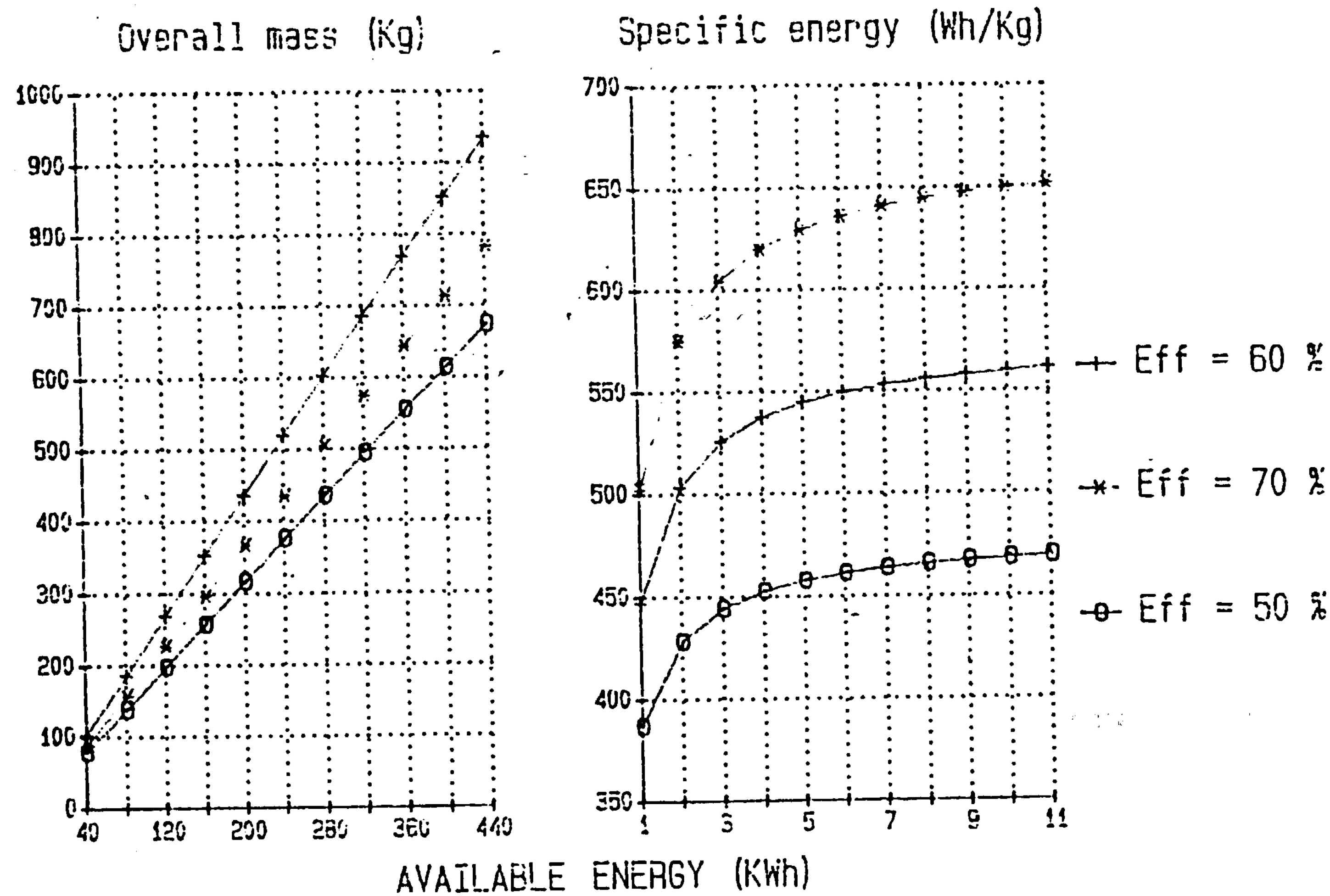
FUEL CELLS (CONT'D)

- OVERALL MASS BETWEEN 680 AND 950 KG
- ENERGY DENSITY BETWEEN 480 AND 650 W/KG ; 140 AND 200 KW/M3
- MOST OF THE MASS DUE TO TANKS EXPECIALLY H_2 TANK.
  HENCE ONLY A FRACTION OF THE MASS CONSUMED DURING OPERATION NEEDS RESUPPLY.
- FLUID MOTION CAN CAUSE PROBLEMS:

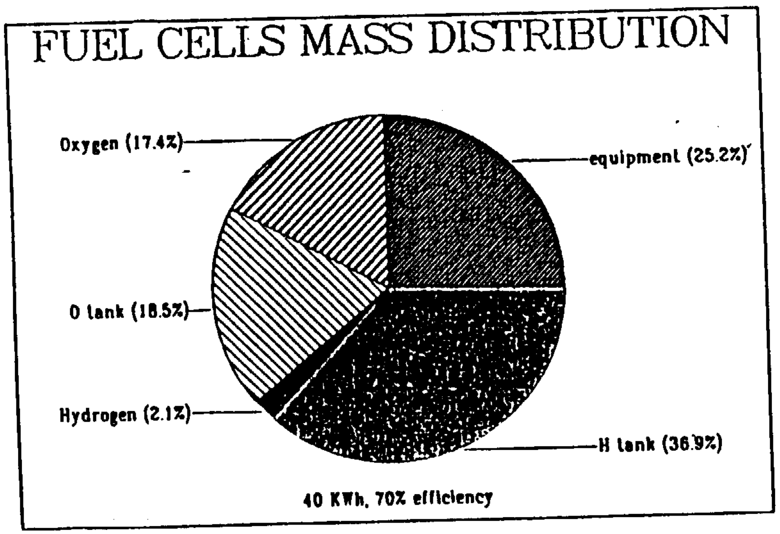
  ELEVATOR CENTER OF MASS SHIFTS
  MECHANICAL NOISE DISTURBING PAYLOAD EXPERIMENTS

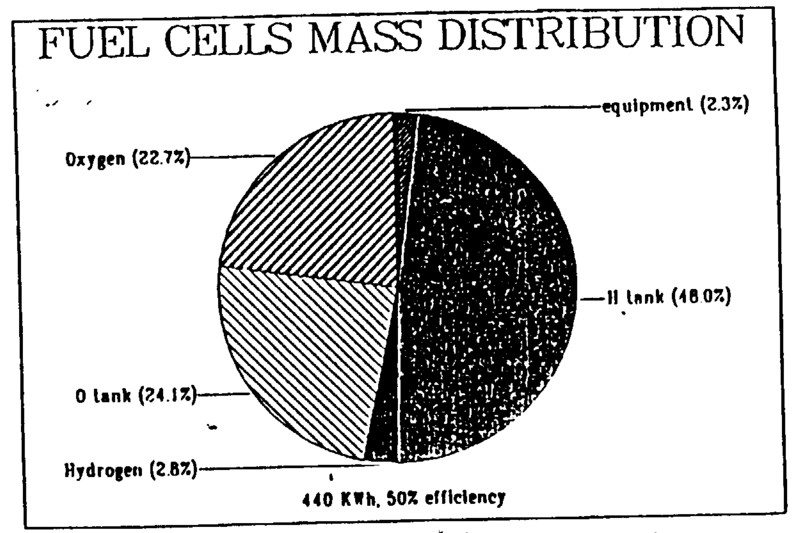
POWER SUBSYSTEM

FUEL CELLS



POWER SUBSYSTEM

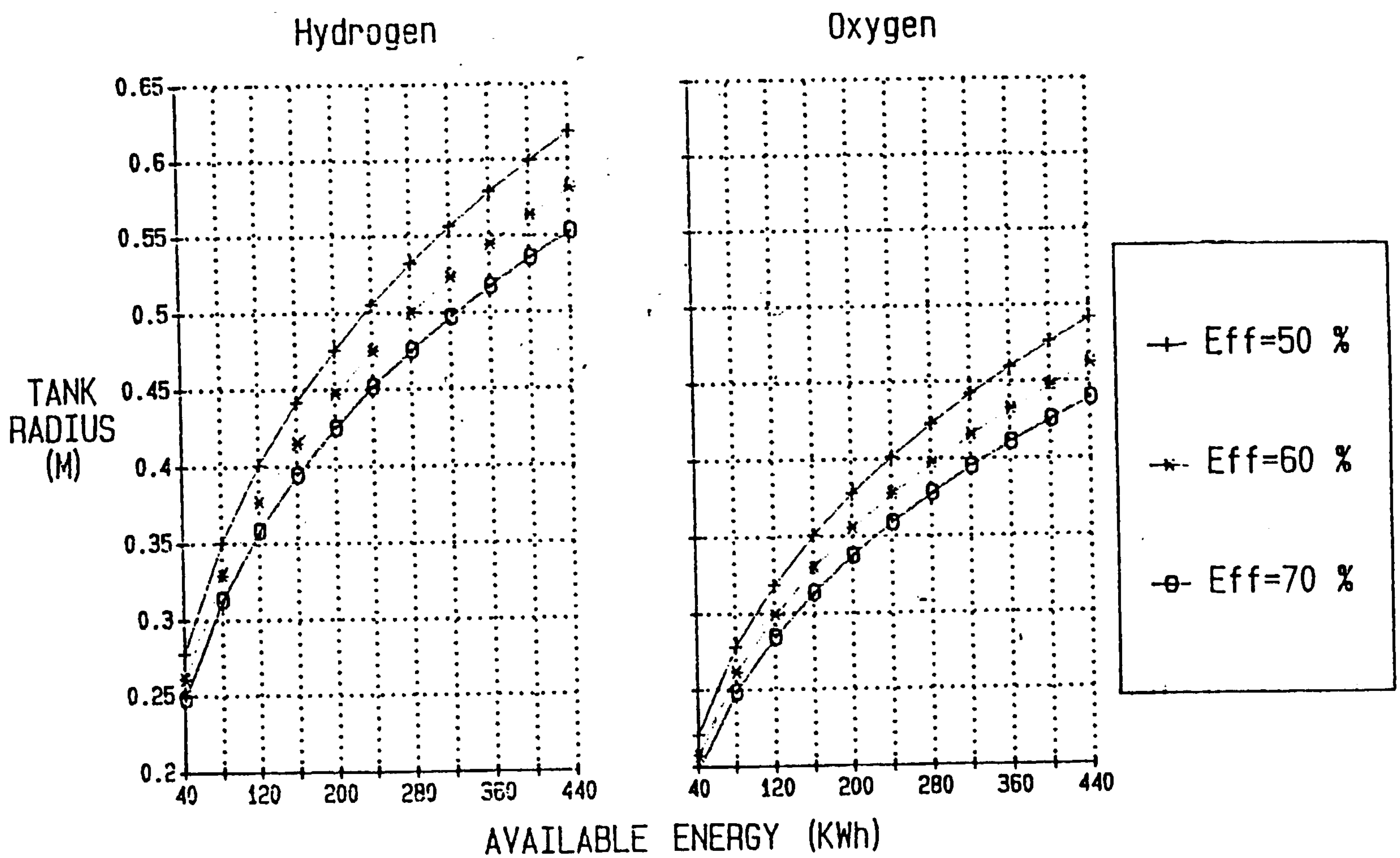




POWER SUBSYSTEM

FUEL STORAGE (CONT'D)

- TWO TANK USED FOR EACH COMPONENT (O_2, H_2, WATER) TO AVOID BALANCE PROBLEM
- H_2 TANKS DIAMETER BETWEEN 0.9 AND 1.2 M
- FURTHER SPLITTING OF GASES AMONG TANKS NOT ADVISED TO AVOID PIPING AND FLUID MANAGEMENT COMPLEXITY INCREASE


Hydrogen
Oxygen
TANK RADIUS (M)
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
40
120
200
280
360
440
AVAILABLE ENERGY (KWh)
Eff=50 %
Eff=60 %
Eff=70 %

POWER SUBSYSTEM

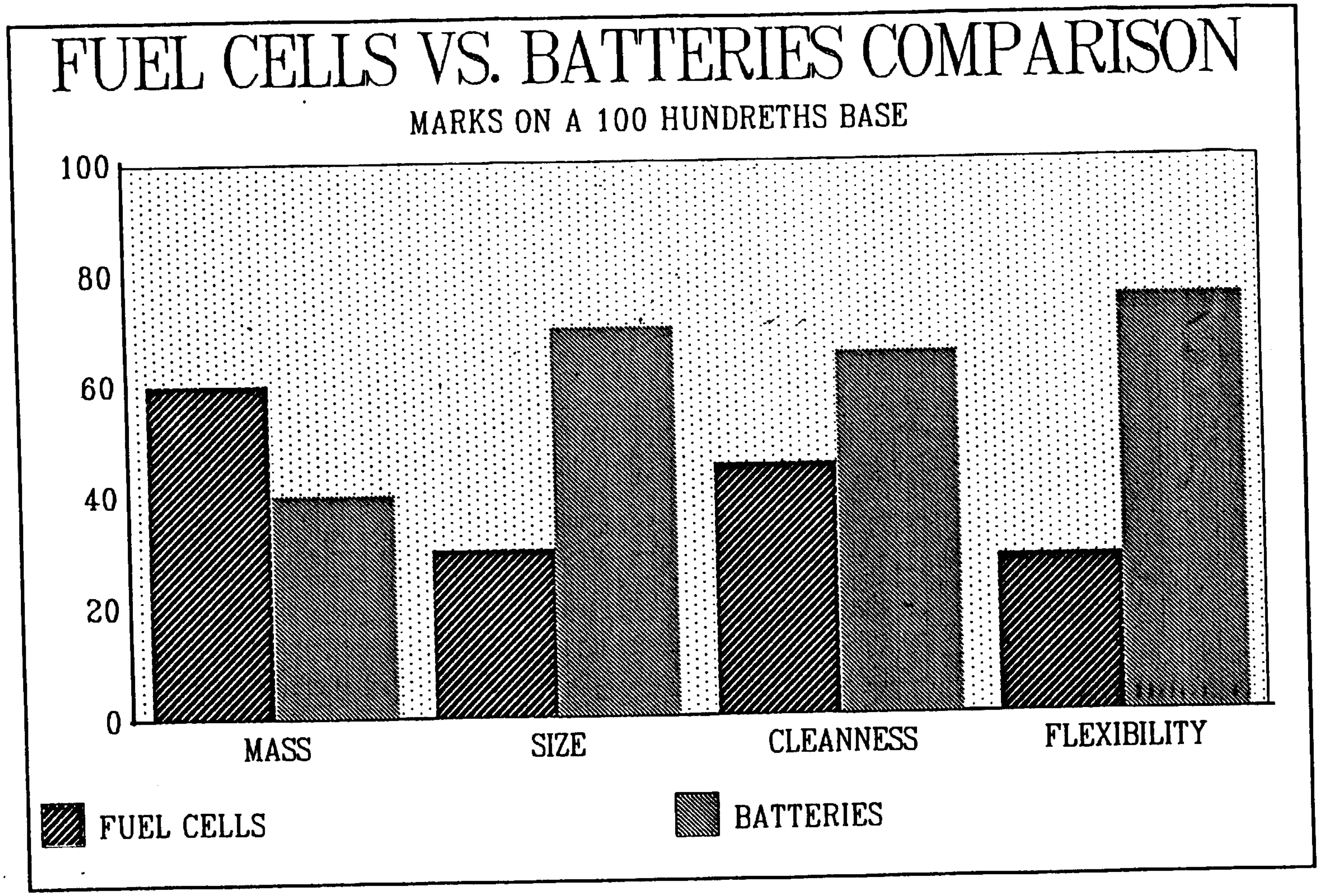
FUEL CELLS/BATTERIES COMPARISON

- o MAIN POINTS

- FUEL CELLS MASS SMALLER (25 %)
- FUEL CELLS VOLUME MUCH BIGGER (SOME HUNDREDS PERCENT)
- CHEMICAL CLEANNESS EQUIVALENT IN THE TWO CASES
  STATIC ENERGY CONVERSION BY BATTERIES CAUSES LESS MECHANICAL NOISE
- BATTERIES MORE ADAPTABLE TO CHANGING PAYLOADS AND MISSION REQUIREMENTS
  FUEL CELLS ADAPTABILITY CONSTRAINED BY TANKS MASS AND VOLUME

- o CONCLUSIONS

- UNDER MOST ASPECTS (EXCEPT FOR MASS) THE BATTERIES ARE FAVOURED IF PERFORMANCES COMPARABLE WITH THOSE OF TERRESTRIAL SYSTEMS ARE ACHIEVABLE

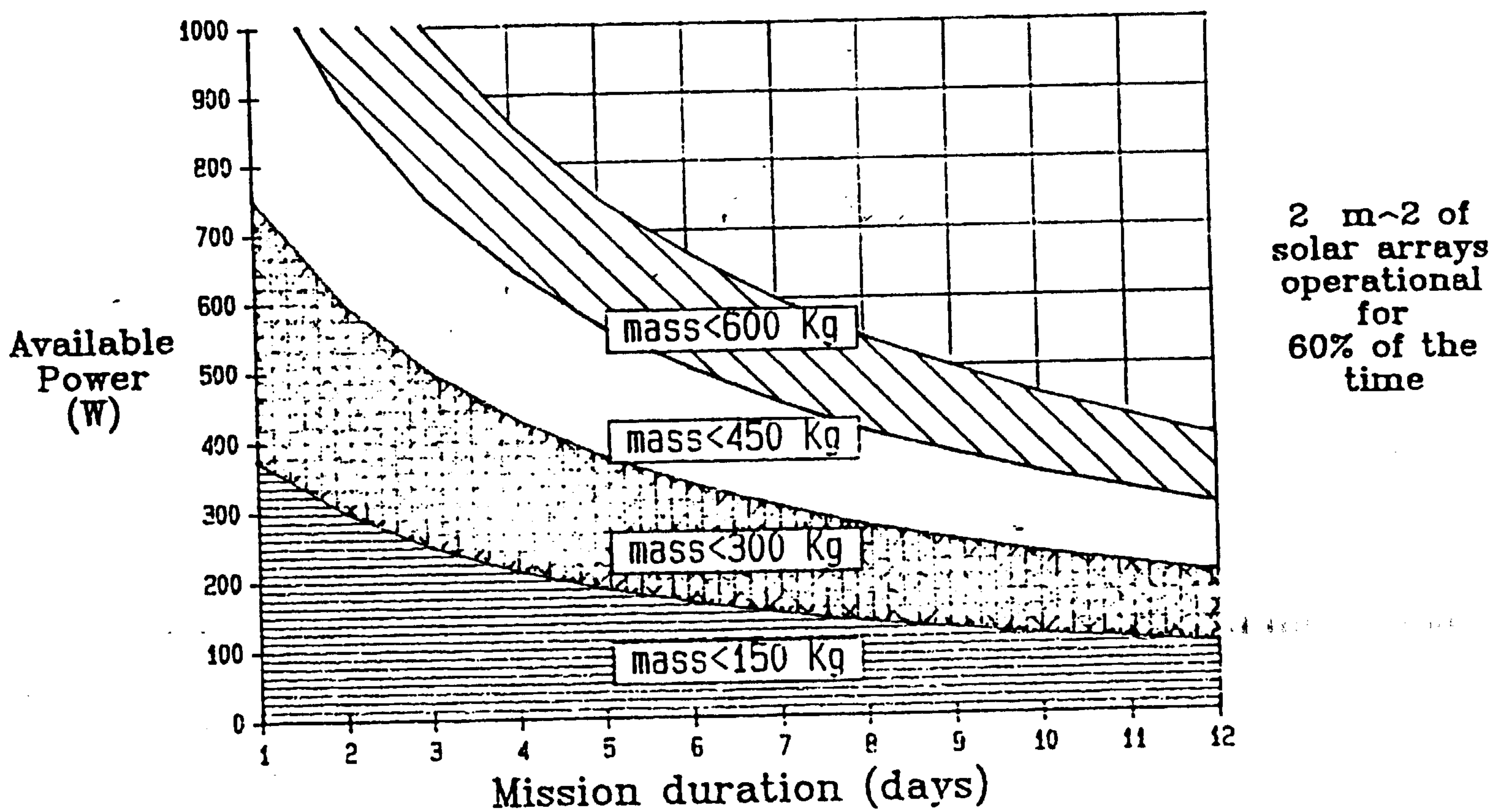

FUEL CELLS VS. BATTERIES COMPARISON
MARKS ON A 100 HUNDRETHS BASE
100
80
60
40
20
0
MASS
SIZE
CLEANNESS
FLEXIBILITY
FUEL CELLS
BATTERIES

POWER SUBSYSTEM

MIXED SYSTEMS

- BODY - MOUNTED SOLAR ARRAYS OFFER TWO ADVANTAGES:
  REDUCE BATTERIES MASS;
  CAN ACT AS BACK - UP IN CASE OF PROLONGED ELEVATOR MISSION
- 2 M^2 OF SOLAR ARRAYS AREA CAN REDUCE BATTERIES MASS TO 500/600 KG FULFILLING REQUIREMENTS OF MOST MISSIONS.

VGL POWER AS A FUNCTION OF BATTERIES MASS AND MISSION DURATION



POWER SUBSYSTEM

CONCLUSIONS

- o POWER TRANSMISSION IS IMPRACTICAL
- o RTG'S TOO "DIRTY" IN TERMS OF RADIATION AND HEAT
- o SOLAR ARRAYS AREA EXCEEDINGLY LARGE
- o BATTERIES AND FUEL CELLS COMPARABLE. BATTERIES PREFERRED IF EARTH TECHNOLOGY TRANSFERABLE TO ELEVATOR APPLICATION.
- o SMALL AMOUNT OF SOLAR ARRAYS HIGHLY ADVISABLE

MAIN FUNCTIONS OF THE VGL ACCELEROMETERS

1) MONITORING THE MICROGRAVITY ENVIRONMENT NEAR THE PAYLOAD DURING THE EXPERIMENT COURSE

2) SUPPORTING THE POSITIONING OPERATIONS OF THE ELEVATOR ALONG THE TETHER AT THE HEIGTH CORRESPONDING TO THE DESIRED GRAVITY LEVEL DURING THE TRANSFER MANOEUVRES (EXPERIMENTS SWITCHED OFF)

AT THE MOMENT IT IS NOT ENVISAGED TO USE ACCELEROMETERS AS SENSORS WITHIN AN AUTO-MATIC CONTROL LOOP OF THE OSCILLATIONS AND THE ATTITUDE OF THE SYSTEM

- FORESEEN ACCELERATIONS OCCURRING ON THE VGL

+

- REQUIREMENTS OF THE SCIENTIST CONCERNING:
  1) RESIDUAL ACCELERATION AMPLITUDE DEPENDANCE ON FREQUENCY DURING THE EXPERIMENTS COURSE
  2) ACCELERATION MEASUREMENT

- ELEVATOR POSITIONING ACCURACY

- REQUIREMENTS ABOUT FULL SCALE, FREQUENCY BAND, ACCURACY, AND RESOLUTION OF THE ACCELEROMETERS

- REQUIREMENTS ABOUT THE DATA ACQUISITION SYSTEM AND THE DATA REDUCTION SYSTEM

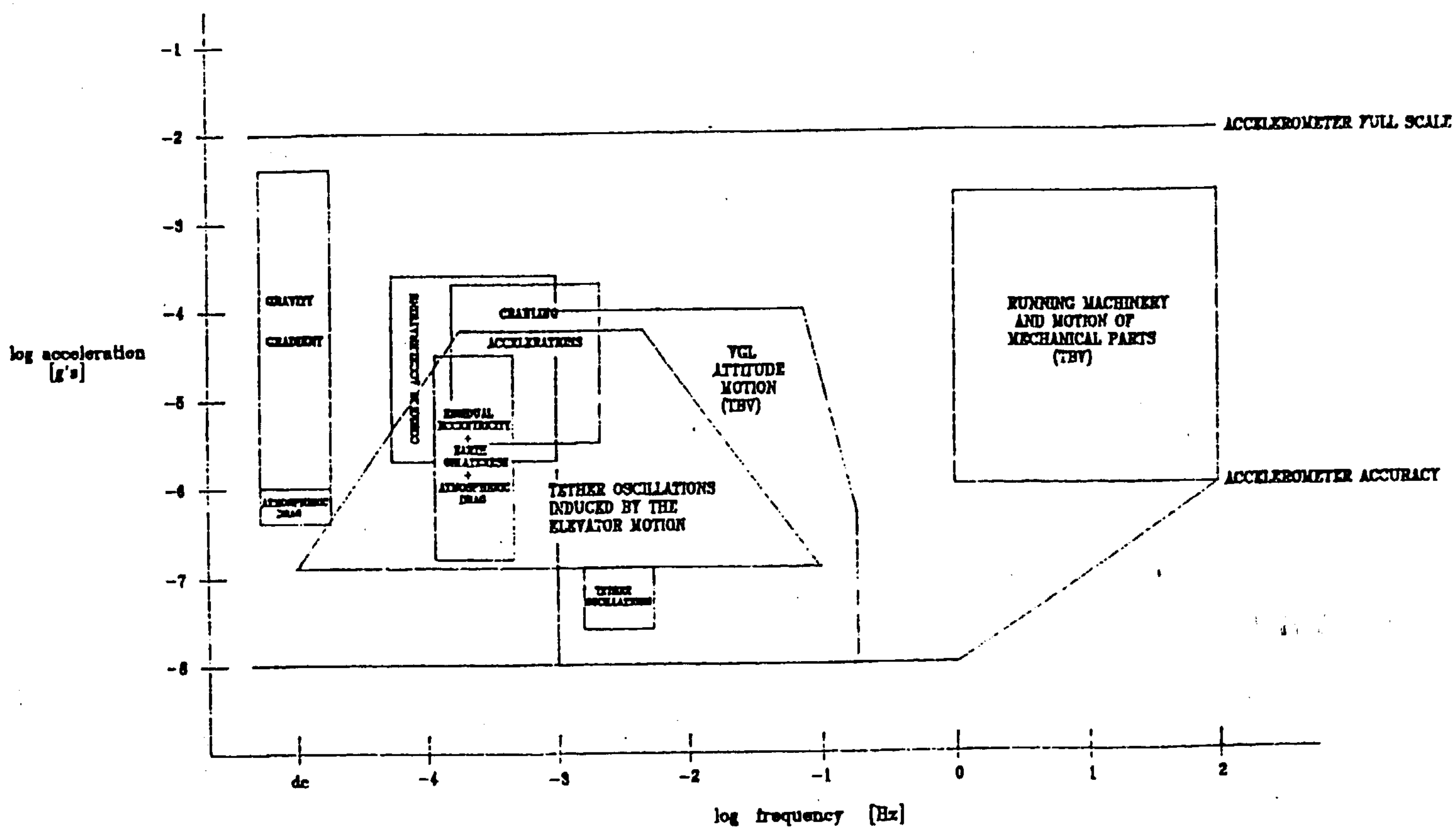
EXPECTED VGL ACCELERATION ENVIRONMENT

- ACCELERATION AMPLITUDE RANGING FROM 10^{-8} TO $5 \cdot 10^{-3}$ G
- ACCELERATION FREQUENCY RANGING FROM 0 TO 100 Hz

ACCELERATION SOURCES

-GRAVITY GRADIENT -ATMOSPHERIC DRAG -ORBITAL PERTURBATIONS -CRAWLING ACCELERATIONS -CORIOLIS ACCELERATIONS -INDUCED TETHER OSCILLATIONS	$0 - 10^{-3}$ Hz
-TETHER OSCILLATIONS (NATURAL AND INDUCED) -VGL ATTITUDE MOTION	$10^{-3} - 10^{-1}$ Hz
-RUNNING MACHINERY AND MOTION OF MECHANICAL PARTS	1 - 100 Hz (TBV)

VGL ACCELERATIONS ENVELOPES AND ACCELEROMETERS ACCURACY PLOT



EXPERIMENTS REQUIREMENTS

- RESIDUAL ACCELERATION DEPENDANCE ON FREQUENCY AS FOLLOWS:

$(0 < \nu < 1\ Hz)$
CONSTANT, WITH DISTURBANCES ALLOWED TO BE WITHIN 10% OF THE NOMINAL VALUE

$(1 < \nu < 100\ Hz)$
MATCHED LINEAR INCREASE WITH FREQUENCY

$(\nu > 100\ Hz)$
MATCHED QUADRATIC INCREASE WITH FREQUENCY

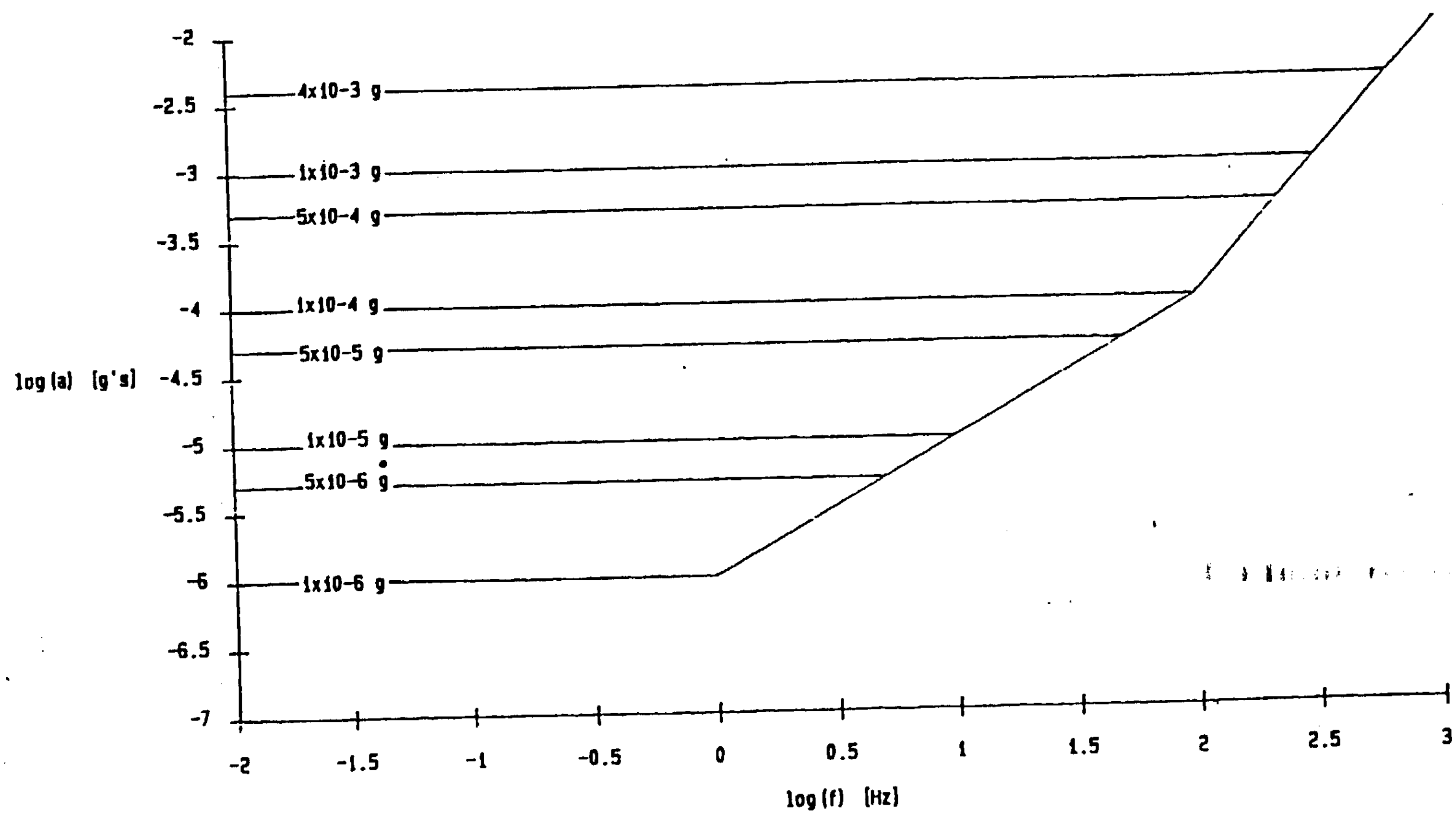
- TRIAXIAL ACCELERATION MEASUREMENT:

RANGE: 10^{-7} TO 10^{-1} G

FREQUENCY BAND: 10^{-2} TO 10^{+2} Hz

ACCURACY: $\leq$ 10% OF THE MEASURE

RESIDUAL ACCELERATION MODULUS DEPENDANCE ON FREQUENCY FOR ANY G-LEVEL



ACCELEROMETERS PACKAGE REQUIREMENTS

MEASUREMENT RANGE: $-10^{-2} - +10^{-2}$ G

FREQUENCY BAND: 0 - 100 Hz

MEASUREMENT ACCURACY: 10^{-8} FROM 0 TO 1 Hz, AND NOT EXCEEDING A LINEAR INCREASE WITH FREQUENCY FROM 1 TO 100 Hz

THE SENSOR RESOLUTION (I.E. ITS INTRINSIC NOISE) MUST BE LOWER (USUALLY AN ORDER OF MAGNITUDE BELOW) THAN THE SMALLEST ACCELERATION TO BE MEASURED. THEREFORE, IN OUR CASE, THE NOISE SPECTRAL DENSITY SHOULD NOT EXCEED $10^{-10} G/\sqrt{Hz}$ IN THE FREQUENCY BAND 0 - 100 Hz, IN ORDER TO GET A RESOLUTION OF 10^{-9} G IN THE SAME BANDWIDTH.

OTHER VERY DESIRABLE FEATURES ARE:

- HIGH DEGREE OF LINEARITY IN BOTH AMPLITUDE AND FREQUENCY RANGE
- GOOD BIAS STABILITY
- LOW TIME-DEPENDANT DRIFT AND TEMPERATURE COEFFICIENT OF THE BIAS

DATA AQUISITION SYSTEM AND DATA REDUCTION SYSTEM REQUIREMENTS

- TO PROVIDE REAL TIME INFORMATIONS ABOUT THE (QUASI -) STEADY COMPONENT OF THE SPECTRUM OF THE OUTPUT SIGNAL DURING THE ELEVATOR TRANFER FROM ONE MICROGRAVITY LEVEL TO ANOTHER, FOR SUPPORTING THE POSITIONING OPERATIONS

- TO PROVIDE A POST REAL TIME RECONSTRUCTION OF THE SPECTRUM OF THE MEASURED ACCELERATIONS IN THE BANDWIDTH 0 - 100 Hz DURING THE EXPERIMENTS COURSE, TO VERIFY THAT THE REQUIRED AMPLITUDE-VS-FREQUENCY PROFILE HAS BEEN MAINTAINED

CURRENTELY AVAILABLE ACCELEROMETERS

<u>MESA</u> (BELL AEROSPACE TEXTRON)

- ELECTROSTATICALLY SUSPENDED CYLINDRICAL PROOF MASS
- AVAILABLE IN BOTH SINGLE-AXIS AND THREE-AXIS VERSION

- FULL SCALE: $\pm 10^{-3}$G TO $\pm 10^{-2}$TYPICALLY
- FREQUENCY BAND: 0 - 10 Hz (ALSO A VERSION WITH A BANDWIDTH OF 50 Hz HAS BEEN BUILT
- RESOLUTION: 10^{-8} G
- SIZE: 9x13x10 cm
- MASS: 3 Kg
- POWER REQUIRED: 15-20 W (MOST OF THE POWER GOES INTO THE OVEN HEATERS, NEEDED FOR THE PROVISION OF A TEMPERATURE CONTROLLED ENVIRONMENT)

- 40 SINGLE-AXIS AND 9 THREE AXIS MESA'S HAVE BEEN BUILT AND FLOWN ON SEVERAL SATELLITE AND ON THE SPACE SHUTTLE

- THE MESA CAN BE PROVIDED WITH MULTIPLE SENSITIVITY RANGES AND WITH AN AUTORANGING CIRCUITRY

CURRENTELY AVAILABLE ACCELEROMETERS (CONT'D)

CACTUS (ONERA)

- ELECTROSTATICALLY SUSPENDED SPHERICAL PROOF MASS
- THREE-AXIS ACCELEROMETER

- FULL SCALE: $\pm 10^{-5}$ G
- RESOLUTION: 10^{-11} G

- THE CACTUS HAS FLOWN IN THE 1975 ON THE CASTOR-D5B SATELLITE

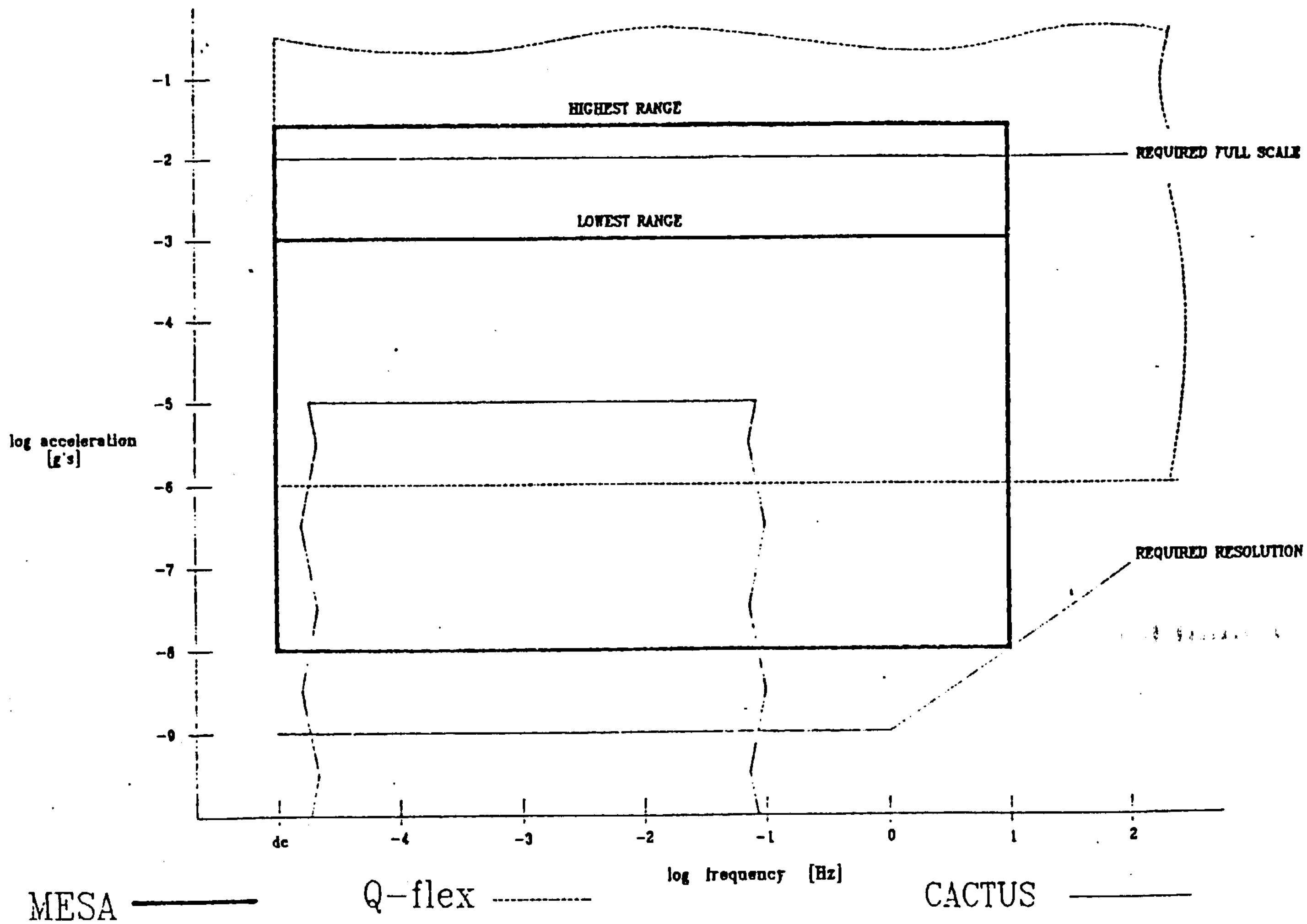
Q-FLEX (SUNDSTRAND)

- TEST MASS ON A QUARTZ HINGE
- SINGLE-AXIS ACCELEROMETER

- FULL SCALE: ± 3 G
- FREQUENCY BAND: 0 - 600 Hz
- RESOLUTION: 10^{-6} G
- SIZE: 2.5x2.5 (DIAMETER) cm
- MASS: 0.08 Kg
- POWER REQUIRED: 0.3 W

- THE RESOLUTION COULD BE IMPROVED DOWN TO 10^{-7} G IF THE SENSOR WAS PROVIDED BY A TEMPERATURE CONTROLLED ENVIRONMENT

FULL SCALE, BANDWIDTH, AND RESOLUTION OF THE CURRENTELY AVAILABLE SENSORS



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ACCELEROMETERS UNDER DEVELOPMENT

MESA IMPROVED (BELL AEROSPACE TEXTRON)

- ELECTROSTATICALLY SUSPENDED CUBIC PROOF MASS
- THREE-AXIS ACCELEROMETER

- FULL SCALE: $\pm 10^{-5}$ G (LOWEST RANGE) $\pm 10^{-2}$ (HIGHEST RANGE) G
- RANGES AVAILABLE: 3 FROM 10^{-2} TO 10^{-5}
- RESOLUTION: 10^{-9} G
- SIZE: 9x13x23 cm
- MASS: 2.27 Kg
- POWER REQUIRED: 9 W
- OPERATING TEMPERATURE: $-23°$C TO $+71°$C

GRADIO (ONERA)

- ELECTROSTATICALLY SUSPENDED CUBIC PROOF MASS
- THREE-AXIS ACCELEROMETER

- FULL SCALE: $\pm 10^{-5}$ G
- INTERNAL NOISE SPECTRAL DENSITY: $10^{-13} G/\sqrt{Hz}$

ACCELEROMETERS UNDER DEVELOPMENT (CONT'D)

SUPERCONDUCTING SIX-AXIS ACCELEROMETER (UNIVERSITY OF MARYLAND)

- MAGNETICALLY LEVITATED SUPERCONDUCTING PROOF MASS
- THREE-AXIS ACCELEROMETER

- EXPECTED INTERNAL NOISE SPECTRAL DENSITY: $4 \cdot 10^{-13} G/\sqrt{Hz}$
- THIS SENSOR HAS TO OPERATE AT CRYOGENIC TEMPERATURE

SOLID STATE ACCELEROMETER (CSEM)

- TRANSDUCER AND CONDITIONING ELECTRONICS REALIZED ON THE SAME SILICON CHIP
- SINGLE-AXIS ACCELEROMETER

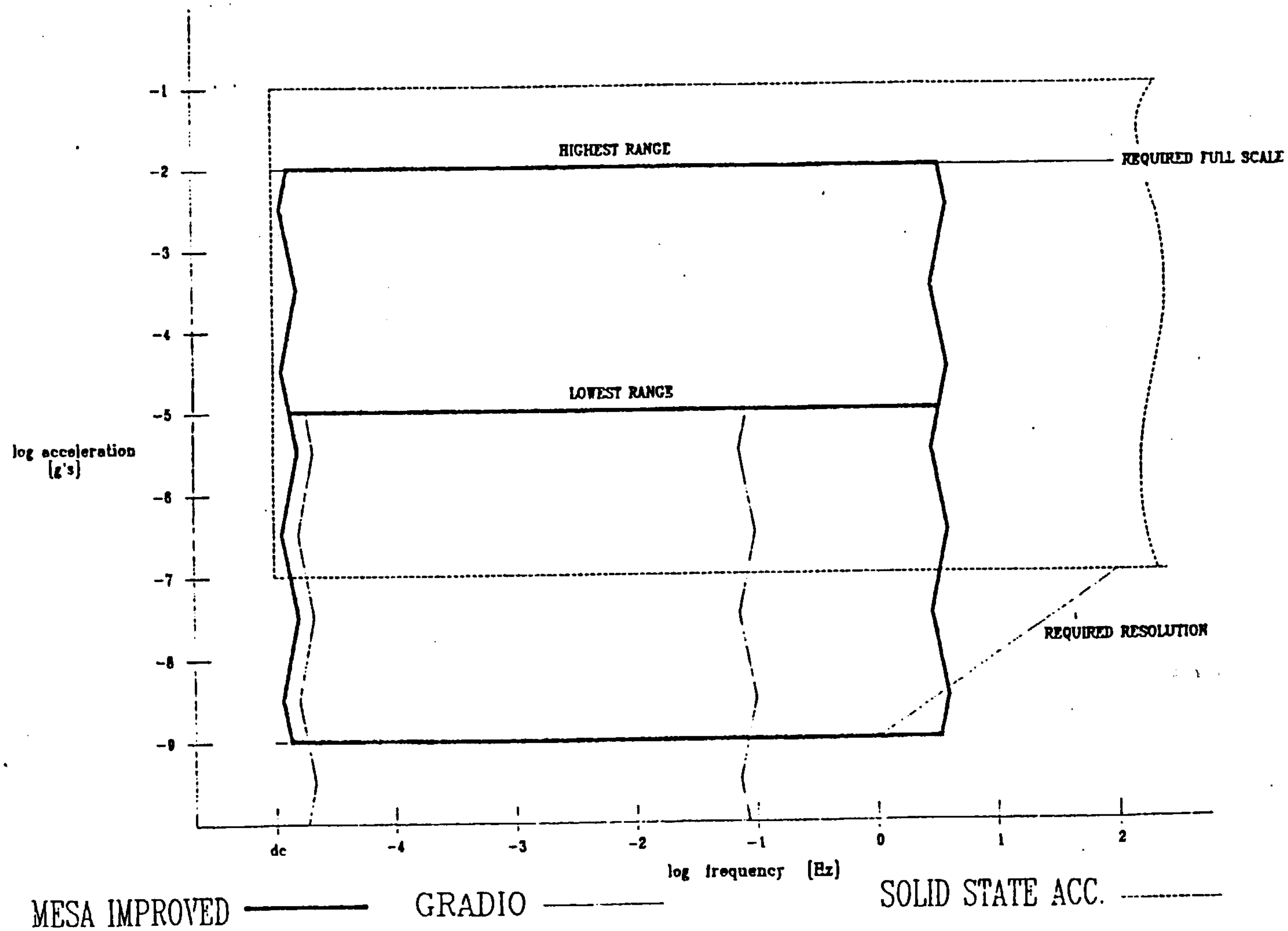
- DYNAMIC RANGE: 10^{6}
- RESOLUTION: $10^{-6} - 10^{-7}$ G
- FREQUENCY BAND: 0 - FEW HUNDREDS OF Hz
- SIZE: 5.4x4.0x1.6 mm

CAVITY LOOKING ACCELEROMETER (HONEYWELL)

- RESONANT FABRY-PEROT OPTICAL CAVITY - SINGLE-AXIS ACCELEROMETER

- EXPECTED RESOLUTION: 10^{-9} G

FULL SCALE, BANDWIDTH, AND RESOLUTION OF THE SENSORS UNDER DEVELOPMENT



CONCLUSIONS

IN VIEW OF THE RESULTS OF THE PRELIMINARY RESEARCH ABOUT ACCELEROMETERS IT IS POSSIBLE TO CONCLUDE THAT THE MAIN PROBLEMS CONCERNING THE MEASUREMENT OF THE ACCELERATION ON BOARD THE VGL ARISE FROM:

1) THE WIDE DINAMIC RANGE CHARACTERIZING THE ACCELERATIONS OCCURRING ON THE ELEVATOR

2) THE SCIENTISTS REQUIREMENTS ON THE MEASUREMENT ACCURACY AND FREQUENCY BAND FOR THE ACCELERATION MONITORING

3) THE NEED OF AN ACCURATE RECONSTRUCTION OF THE ACCELERATION SPECTRUM, AND ESPECIALLY OF THE LOW-FREQUENCY COMPONENTS

IN FACT:

NO ONE OUT OF THE CONSIDERED ACCELEROMETERS (BOTH AVAILIBLE AND UNDER DEVELOPMENT) IS ABLE TO FULFILL ALL THE STATED REQUIREMENTS

THE ACCURATE DETECTION OF THE STEADY-STATE OR SLOWLY VARYING ACCELERATIONS WITHIN ACCELEROMETER READOUTS CONTAINING 10 - 100 Hz FREQUENCY SIGNALS IS STILL AN UNSOLVED PROBLEM.

CONCLUSIONS (CONT'D)

POSSIBLE SOLUTION

TO SPLIT THE AMPLITUDE AND FREQUENCY RANGES IN INTERVALS OF SMALLER AMPLITUDE TO BE COVERED BY DIFFERENT SENSORS (FOR INSTANCE, AN ACCELEROMETER WITH A SENSITIVE BAND-WIDTH 0 - 10^{-4} Hz COULD PROVIDE, IN REAL TIME, THE VALUE OF THE GRAVITY GRADIENT INSIDE THE VGL)

SENSORS SELECTION

FIRST POSSIBILITY:

TO MAKE USE OF SENSORS AMONG THOSE UNDER DEVELOPMENT
OR
TO DESIGN AND DEVELOP NEW SENSOR(S) TAILORED ON THE STATED REQUIREMENTS

SECOND POSSIBILITY:

TO RELAX THE REQUIREMENTS ABOUT THE MEASUREMENT ACCURACY, THE SENSOR RESOLUTION, AND THE FREQUENCY BAND SO AS TO MAKE POSSIBLE THE USE OF AVAILABLE HARDWARE (FOR INSTANCE, BY REDUCING THE ACCURACY DOWN TO 50% OF THE MEASURE, THE SENSOR RESOL-UTION TO HALF AN ORDER OF MAGNITUDE BELOW THE SMALLEST SIGNAL, AND THE FREQUENCY BAND TO 0 - 10 Hz, THE MESA ONLY COULD BE SUFFICIENT FOR MEETING ALL THE REQUIREMENTS)

TETHERED GRAVITY LABORATORIES
MID TERM REVIEW
TORINO, ITALY
26-28 SEPTEMBER 1989

STUDIES CARRIED OUT AT THE SMITHSONIAN ASTROPHYSICAL OBSERVATORY

Presented by

Enrico C. Lorenzini

Work Done Under:
Aeritalia Contract 8864153

Smithsonian Astrophysical Observatory
Cambridge, MA 02138

ACTIVE CENTER OF GRAVITY CONTROL

HIGHLIGHTS FROM THE FIRST STATUS REVIEW

SUMMARY

- THE DYNAMICS OF THREE TETHERED CONFIGURATIONS PROPOSED BY AERITALIA HAS BEEN ANALYZED, NAMELY:

  - DOUBLE TETHER CENTERED SYSTEM (DTCS)
  - SINGLE TETHER SYSTEM (STES)
  - DOUBLE TETHER SYSTEM WITH SPACE ELEVATOR (DTSSE)

- THE DYNAMIC RESPONSE AND THE APPARENT ACCELERATIONS LEVELS ON THE SPACE STATION AND ON THE SPACE ELEVATOR, IN DTSSE CASE, HAVE BEEN EVALUATED FOR EACH CONFIGURATION ACTED UPON BY ENVIRONMENTAL PERTURBATIONS

- THE EFFECTIVENESS OF LONGITUDINAL DAMPERS ON THE G-QUALITY OF THE ACCELERATION LEVELS HAS BEEN ASSESSED

- THE CAPABILITY OF A TETHERED SYSTEM IN DAMPING THE FIRST FLEXURAL MODE OF THE SINGLE-TRANSVERSE-BOOM SPACE STATION HAS BEEN INVESTIGATED

NUMERICAL SIMULATIONS

- THE DYNAMICS OF THE THREE TETHER SYSTEMS HAS BEEN ANALYZED BY MEANS OF SAO NUMERICAL CODE

- ALL THE SIMULATION HAVE BEEN RUN WITH THE SYSTEM INITIALLY ALIGNED WITH THE LOCAL VERTICAL AND THE SPACE STATION AT 352 KM OF ALTITUDE

- ORBITAL PARAMETERS

  - INCLINATION 28.5°
  - INITIAL ANOMALY 180°
  - SUN AT THE SUMMER SOLSTICE

- THE DURATION OF THE SIMULATIONS IS 8000 SEC (1.5 ORBITS) OR 22,000 SEC (4 ORBITS)

- ENVIRONMENTAL PERTURBATIONS

  - GRAVITY (J_o+J_2)
  - ATMOSPHERIC DRAG
  - THERMAL MODEL OF THE WIRE

DOUBLE TETHER CENTERED SYSTEMS (DTCS)

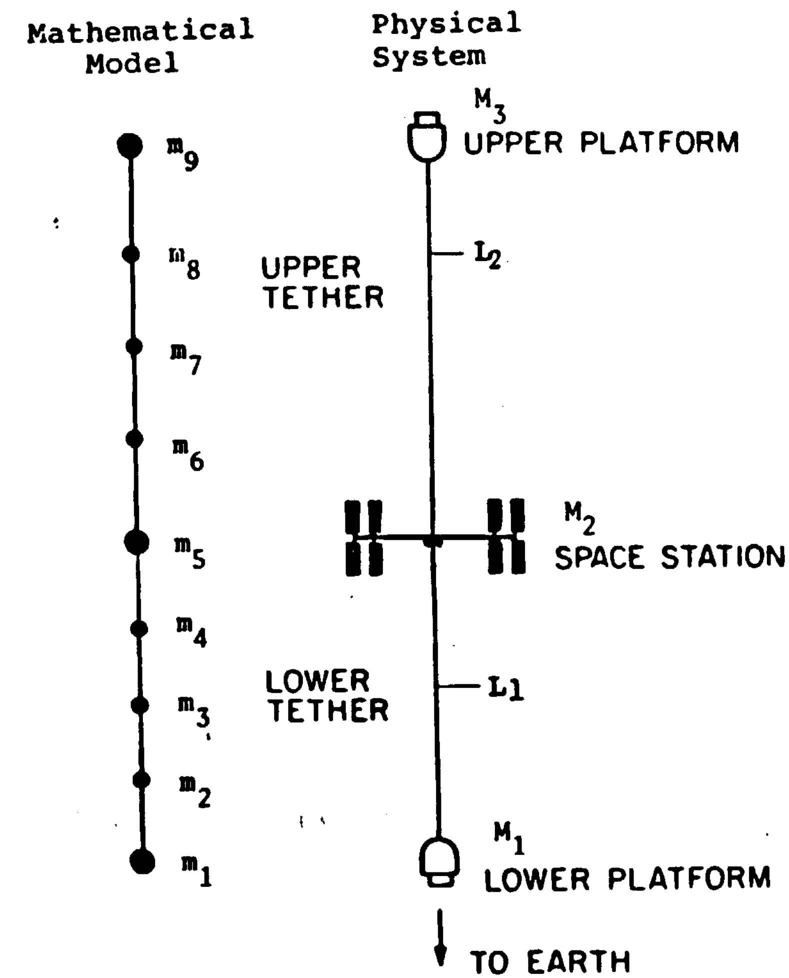
- SYSTEM CHARACTERISTICS

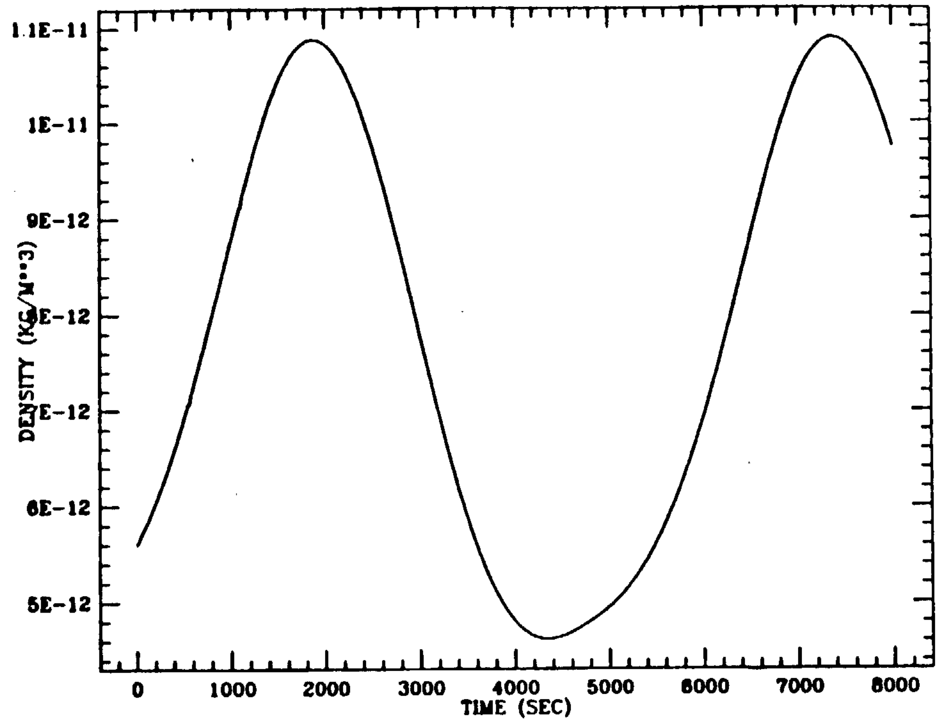
$M_1 = 3050$ kg
$M_2(SS) = 200 \times 10^3$ kg
$M_3 = 5400$ kg

- ALUMINUM TETHERS

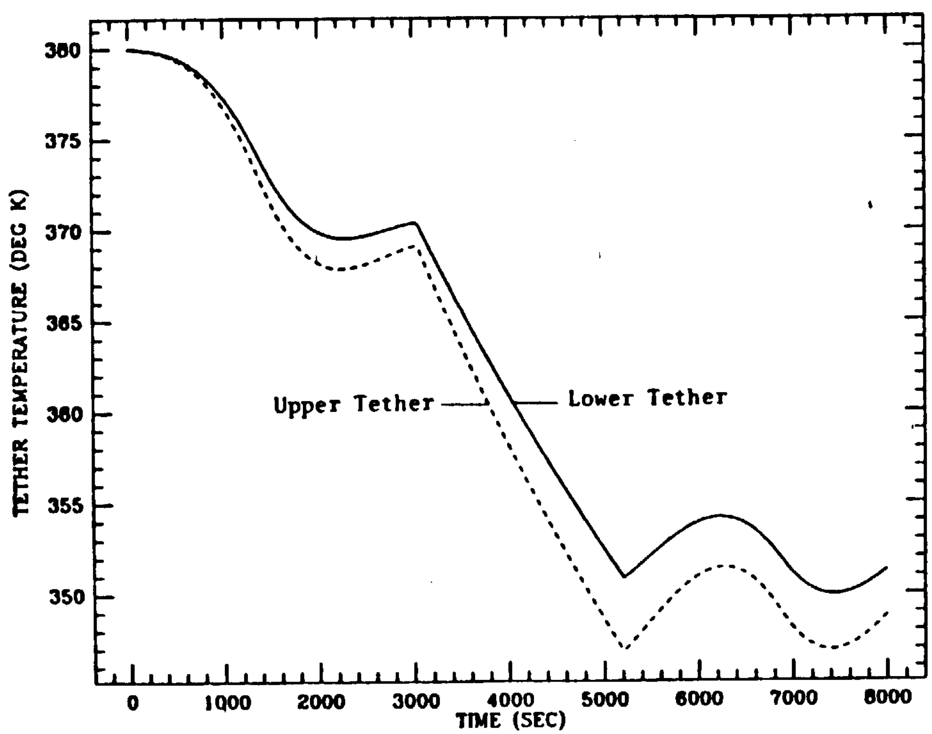
$\ell_1 = 8360\ m; \quad M_{T1} = 2490\ kg;$ diam. = 0.012 m

$\ell_2 = 600\ m; \quad M_{T2} = 1191\ kg;$ diam. = 0.001 m

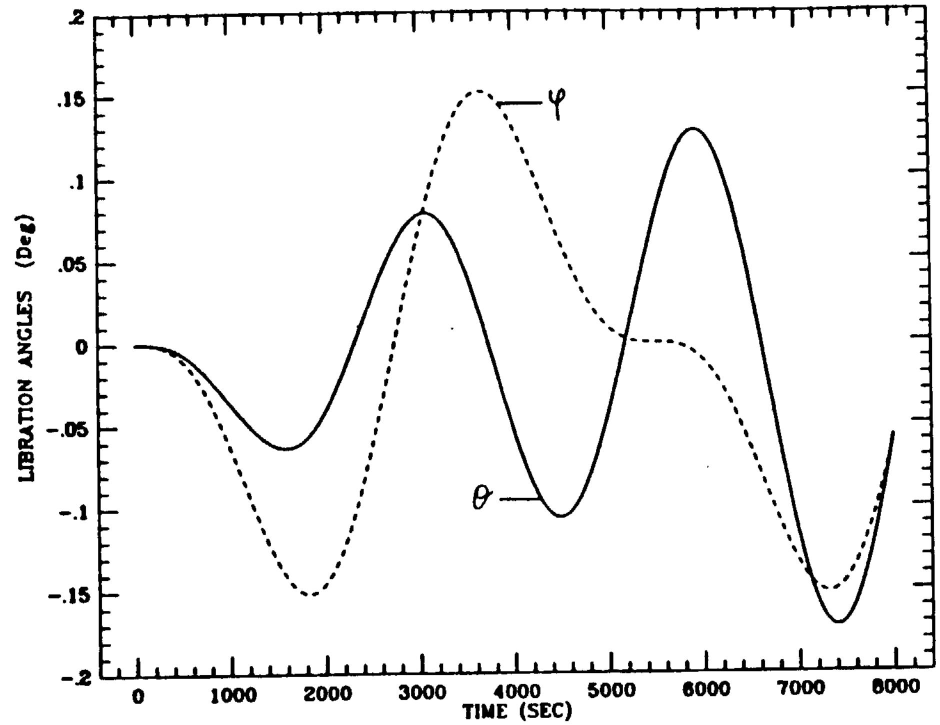


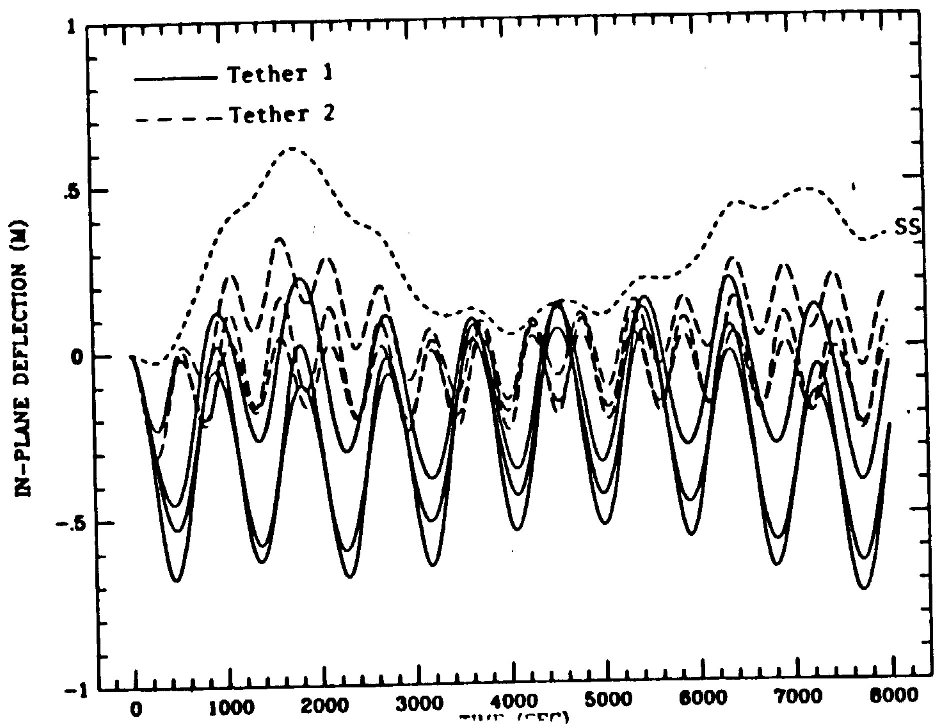


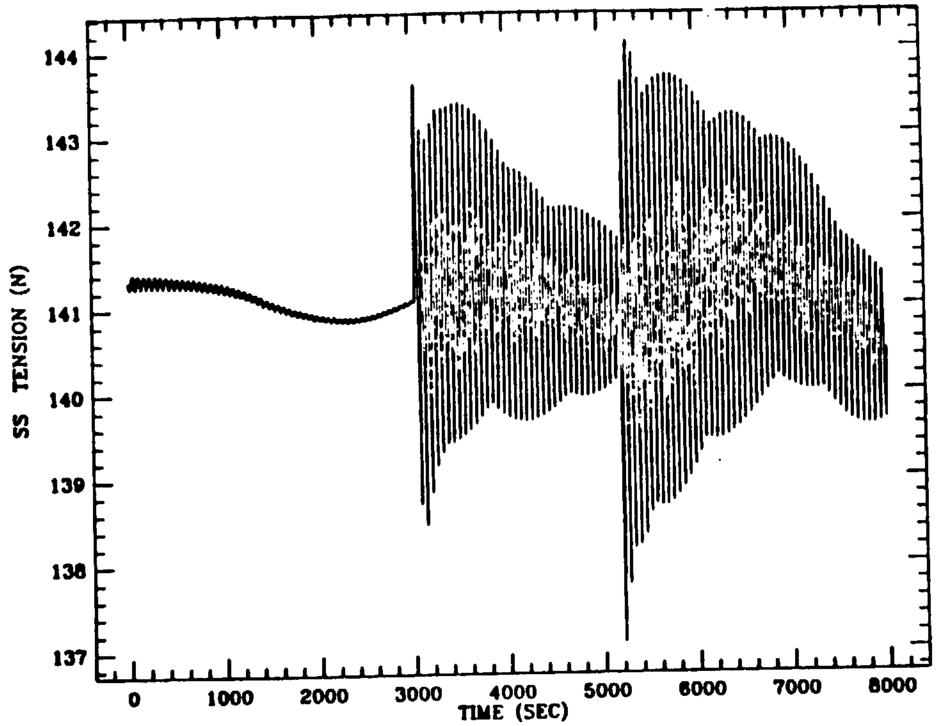
1.1E-11
1E-11
9E-12
6E-12
5E-12
DENSITY (KG/M**3)
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)

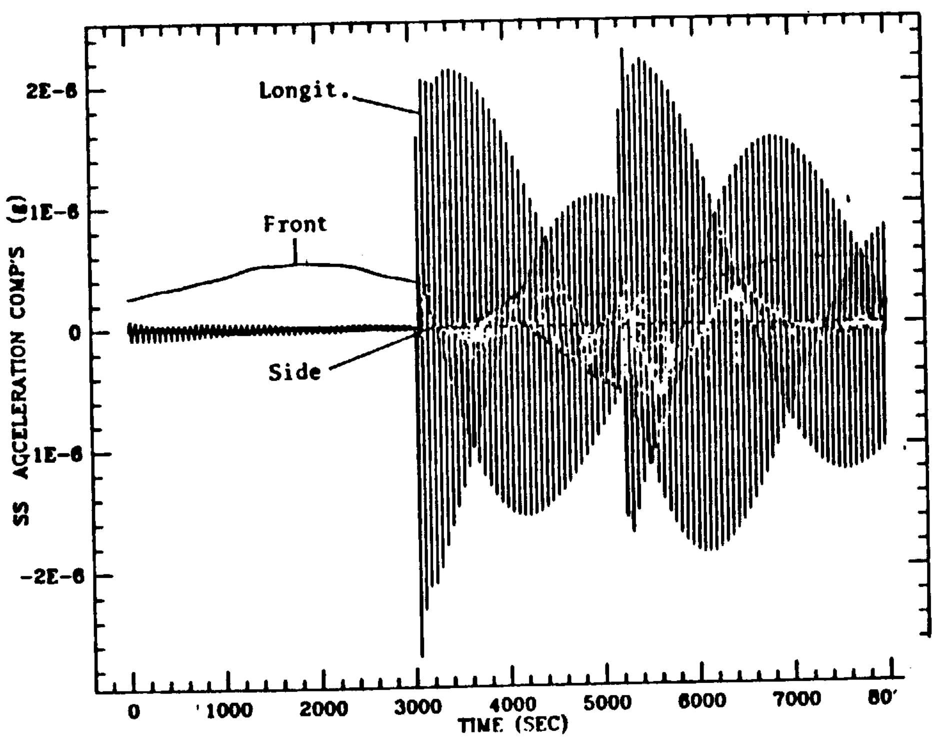


380
375
370
365
360
355
350
TETHER TEMPERATURE (DEG K)
Upper Tether
Lower Tether
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)


LIBRATION ANGLES (Deg)
.2
.15
.1
.05
0
-.05
-.1
-.15
-.2
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)
φ
θ


IN-PLANE DEFLECTION (M)
1
.5
0
-.5
-1
Tether 1
Tether 2
SS
0
1000
2000
3000
4000
5000
6000
7000
8000


SS TENSION (N)
144
143
142
141
140
139
138
137
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)


SS ACCELERATION COMP'S (g)
2E-6
1E-6
0
1E-6
-2E-6
Longit.
Front
Side
0
1000
2000
3000
4000
5000
6000
7000
TIME (SEC)

NOISE ABATEMENT

- DAMPING OF SYSTEM OSCILLATIONS IS ESSENTIAL TO PROVIDE ACCELERATION LEVELS ON BOARD THE LABORATORIES SUITABLE FOR MICROGRAVITY EXPERIMENTS

- THE CONTROL OF THE SYSTEM LIBRATIONS CAN BE SWITCHED OFF WITHOUT IMPAIRING THE MICROGRAVITY EXPERIMENTS ONCE THE TRANSIENT OSCILLATIONS HAVE BEEN DAMPED (e.g. POST-DEPLOYMENT PHASE)

- ON THE CONTRARY LONGITUDINAL OSCILLATIONS, EXCITED PERIODICALLY BY THERMAL PERTURBATIONS (TWICE PER ORBIT), MUST BE CONTINUOUSLY CONTROLLED

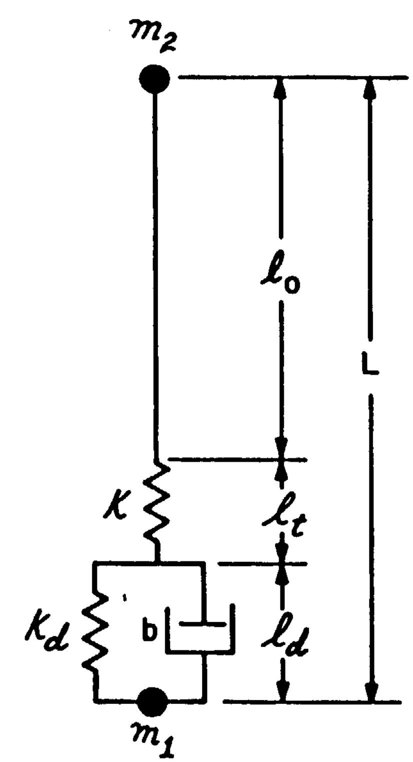
- SAO HAS DEVISED A SIMPLE TECHNIQUE FOR DAMPING LONGITUDINAL VIBRATIONS WHICH MAKE USE OF DAMPERS MOUNTED IN SERIES WITH THE TETHER SEGMENTS.

DAMPING OF LONGITUDINAL OSCILLATIONS

- THE DAMPER CAN BE SCHEMATICALLY REPRESENTED AS A SPRING-DASHPOT DEVICE WITH SPRING CONSTANT K_d AND DAMPING COEFFICIENT b

- THE STUDY OF THE DAMPER HAS BEEN CARRIED OUT UNDER THE FOLLOWING ASSUMPTIONS
  - MASSLESS DAMPER
  - 2 DOF SYSTEM, NAMELY TETHER STRETCH ℓ_t AND DAMPER STRETCH ℓ_d
  - MASSLESS BUT ELASTIC TETHERS

- THE EQUATIONS OF MOTION ARE AMENABLE TO ANALYTIC SOLUTION BY MEANS OF LAPLACE TRANSFORMATION

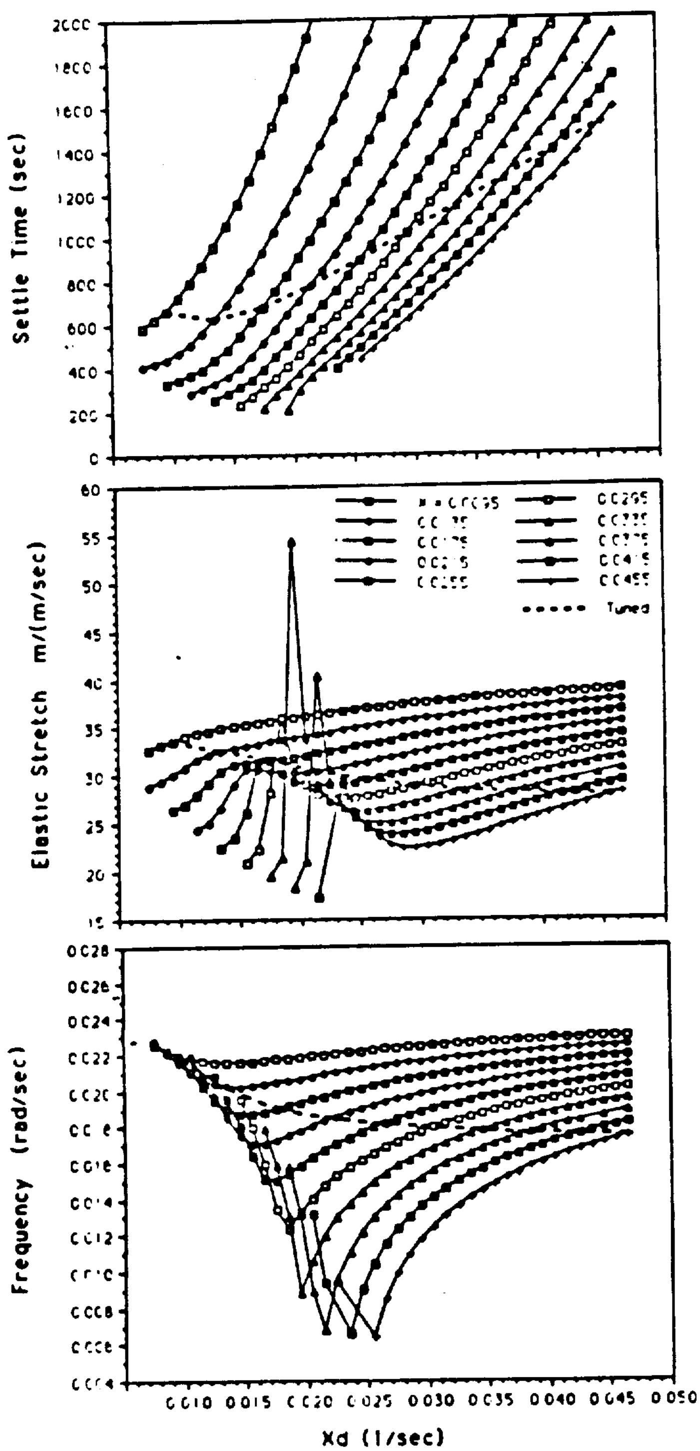


DAMPING OF LONGITUDINAL OSCILLATIONS

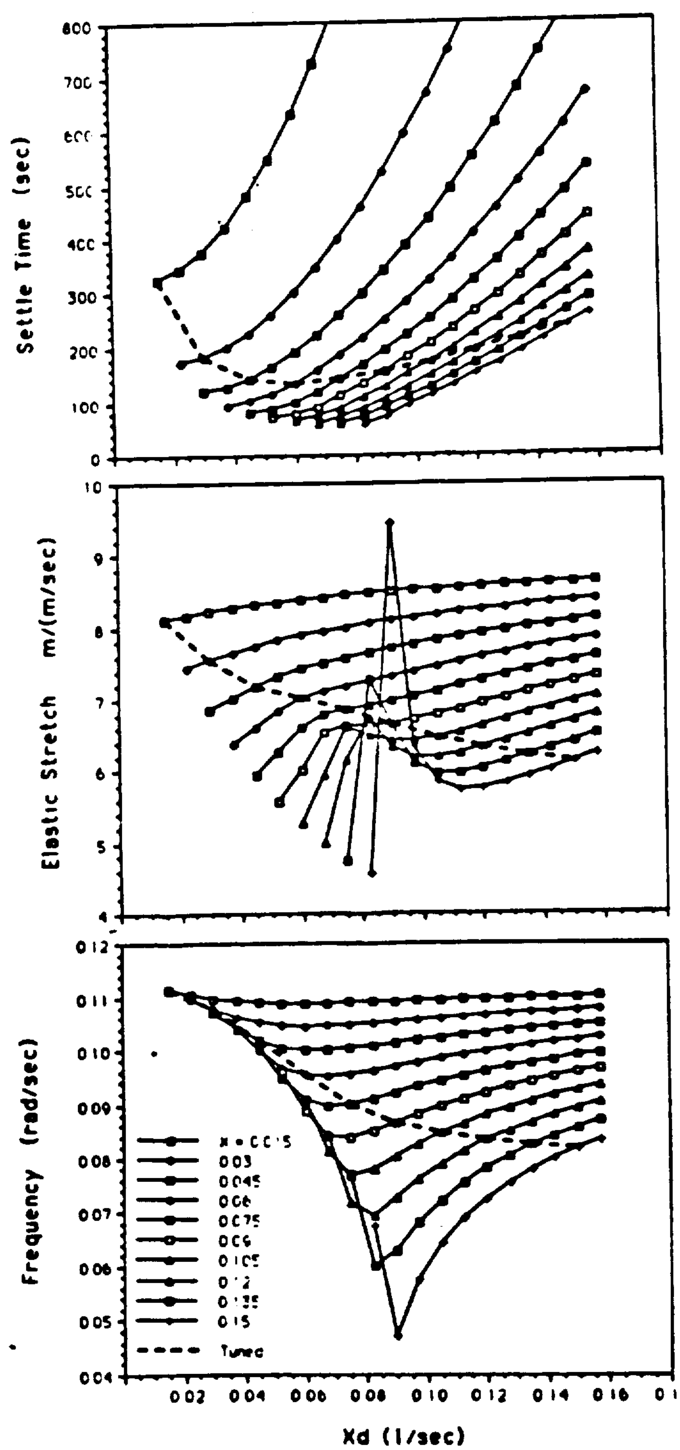
- THE RESPONSE OF THE SYSTEM TO THE IMPULSE HAS BEEN COMPUTED
- A PARAMETRIC STUDY HAS BEEN CARRIED OUT WITH $\omega_o = \sqrt{\frac{k}{M_{EQ}}}$, $X_D = k_D/b$, $X = k/b$

  AS PARAMETERS, IN ORDER TO DESIGN THE DAMPER THAT PROVIDES THE SMALLEST AND/OR SHORTEST FLUCTUATION OF THE ACCELERATION
- THE SETTLE TIME T_S AND THE ELASTIC STRETCH ℓ_t (DIRECTLY RELATED TO THE ACCELERATION) HAVE BEEN CHOSEN AS INDICATORS OF THE DAMPER EFFECTIVENESS
- A TUNED DAMPER ($X=X_D$) PROVIDES A "CLOSE TO OPTIMAL" SETTLE TIME AND AN ELASTIC STRETCH (i.e. ACCELERATION) SMALLER THAN AN OPTIMAL "NON-TUNED" DAMPER
- FOR A TUNED DAMPER THE FASTEST OSCILLATION DECAY IS OBTAINED FOR A VALUE OF THE DAMPING COEFFICIENT WHICH PROVIDES A DAMPING RATIO OF 0.9 FOR THE 1-DOF "DAMPER + MASS" SYSTEM

– KEVLAR; M_{EQ} = 9677 k_g; ℓ = 10500 m; ω = 0.0242 rad/sec (f = 0.004 Hz)



– KEVLAR; M_{EQ} = 4918 kg; ℓ = 1000 m; ω = 0.117 rad/sec (f = 0.019 Hz)



DAMPING OF LONGITUDINAL OSCILLATIONS

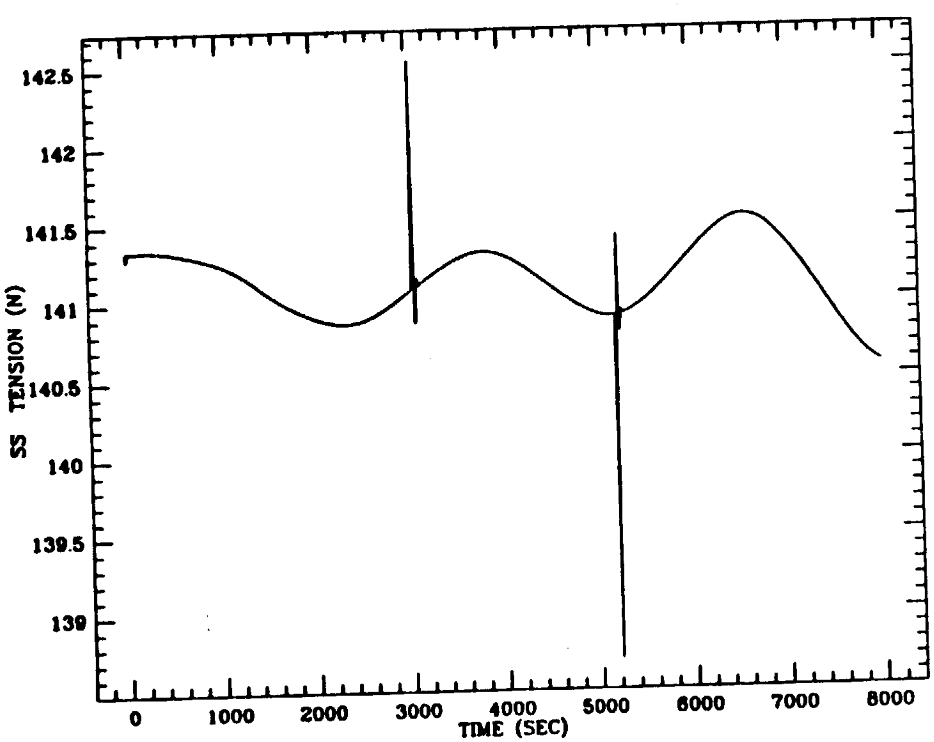
- FOR “SOFT” TETHERS (e.g. SMALL DIAM.) THE DAMPER ALGORITHM MUST BE IMPLEMENTED IN THE ACTUATORS OF THE TETHERS’ REELING MECHANISMS (ACTIVE CONTROL), SINCE THE LONGITUDINAL STRETCH IS LARGE

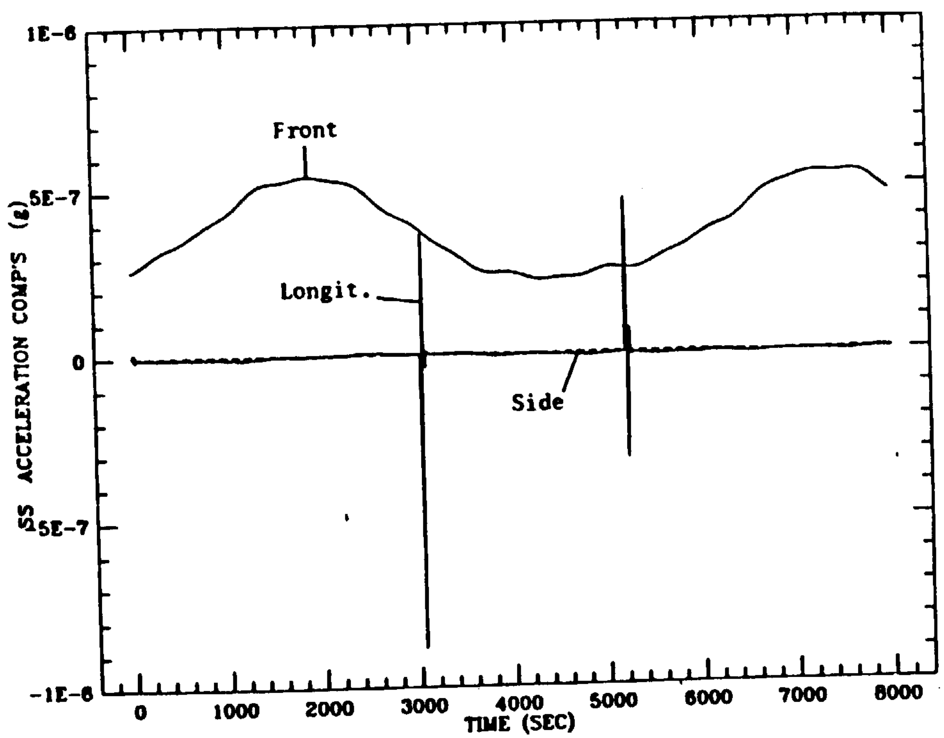
- FOR “STIFF” TETHERS (e.g. LARGE DIAM.) THE DAMPER MAY SIMPLY BE A SPRING DASHPOT DEVICE, SINCE THE STRETCH IS AT MOST FEW CENTIMETERS LONG

- DAMPER CHARACTERISTICS
  - FREQUENCY ω TUNED TO ASSOCIATED TETHER BOBBING FREQUENCY
  - DAMPING COEFFICIENT $b = 1.8\ EA/(\omega\ell)$

DTCS WITH TWO TUNED DAMPERS

- LOWER TETHER: $\omega_{D1} = 0.4927$ rad/sec; $b_{d1} = 3707$ N/(m/sec)
- UPPER TETHER: $\omega_{D2} = 0.4113$ rad/sec; $b_{d2} = 4927$ N/(m/sec)





DTCS DYNAMICS: RESULTS

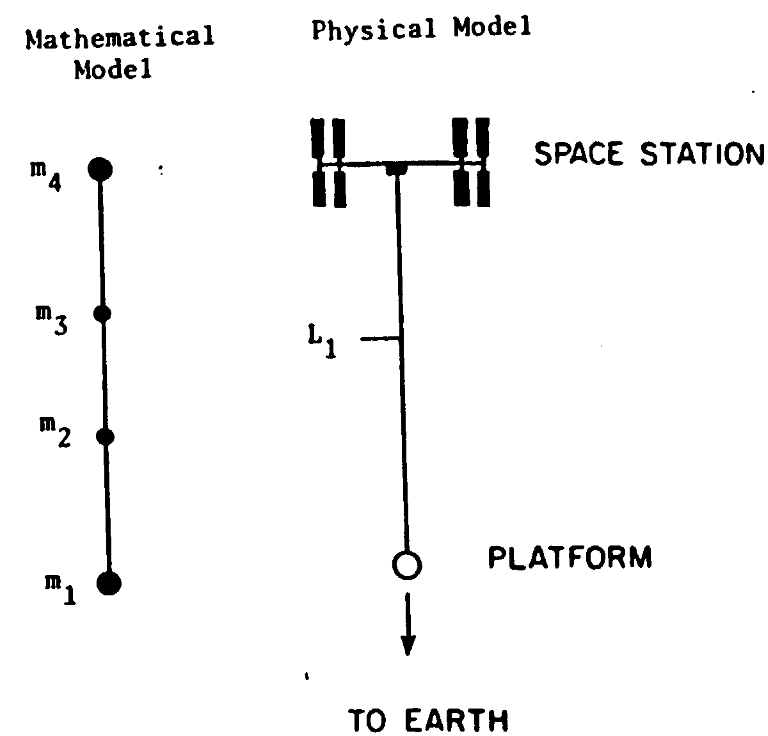
- THE EFFECTIVENESS OF THE DAMPERS IS EVIDENT: THE LONGITUDINAL OSCILLATIONS ARE RAPIDLY REDUCED TO ZERO AFTER THE TERMINATOR CROSSING

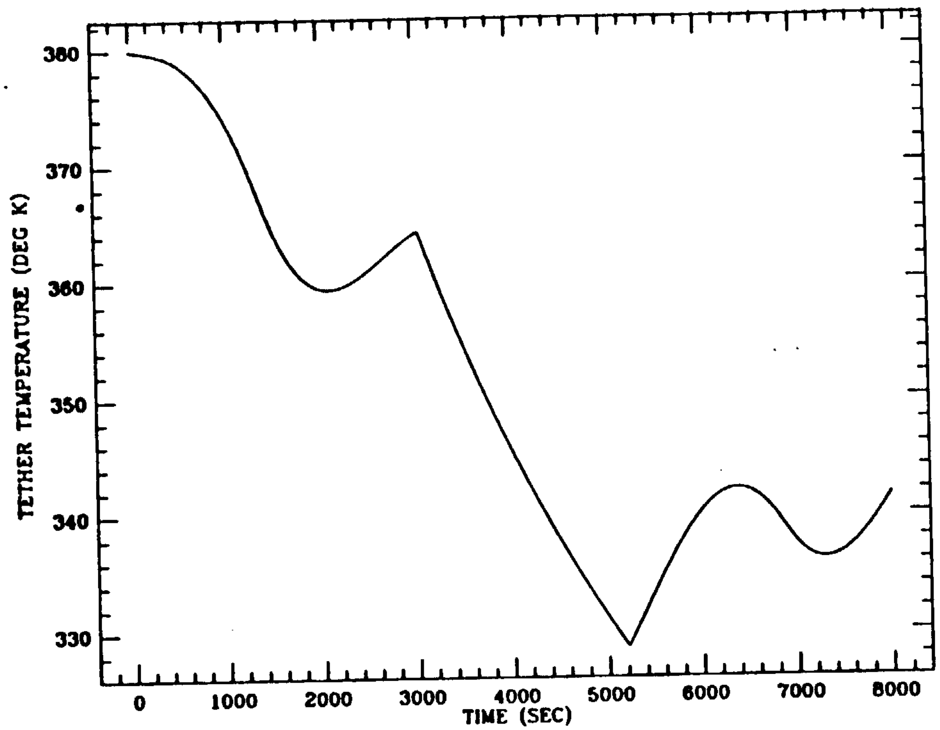
- THE VALUES OF THE PEAKS ARE REDUCED TO A VALUE COMPARABLE TO THE FRONT ACCELERATION COMPONENT

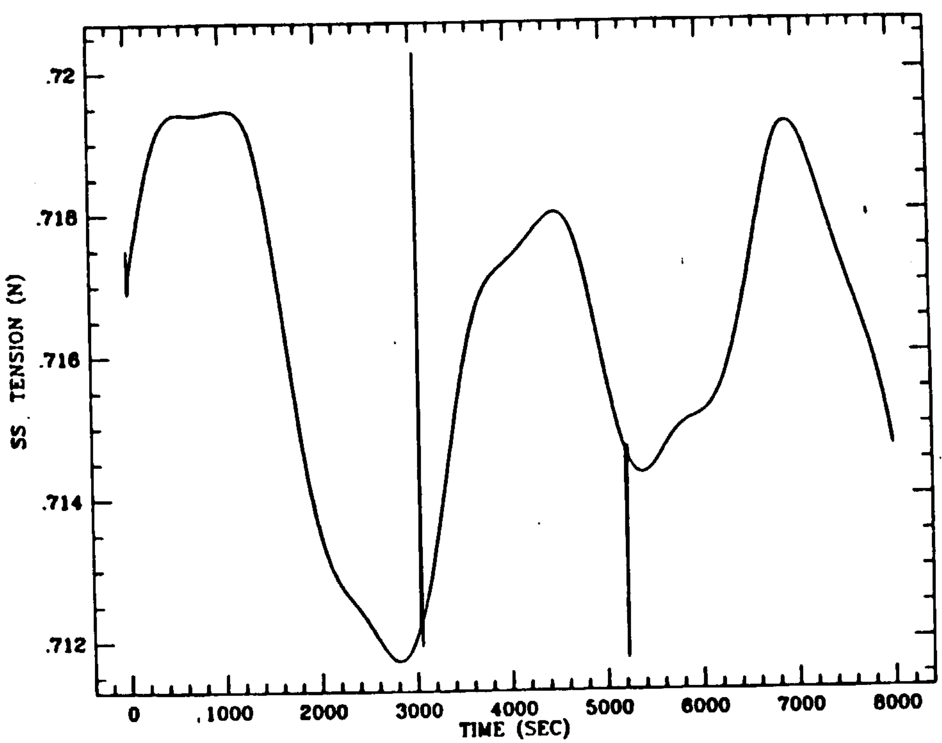
- THE MAXIMUM ACCELERATION ON BOARD THE SS IS ALWAYS SMALLER THAN 10^{-6} g

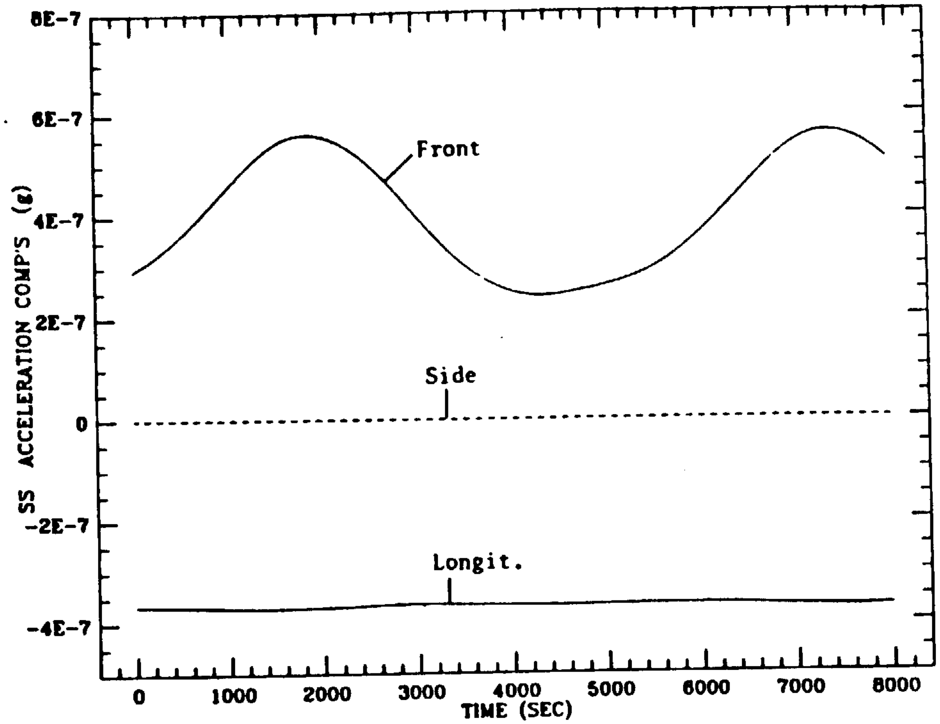
SINGLE TETHER SYSTEM (STES)

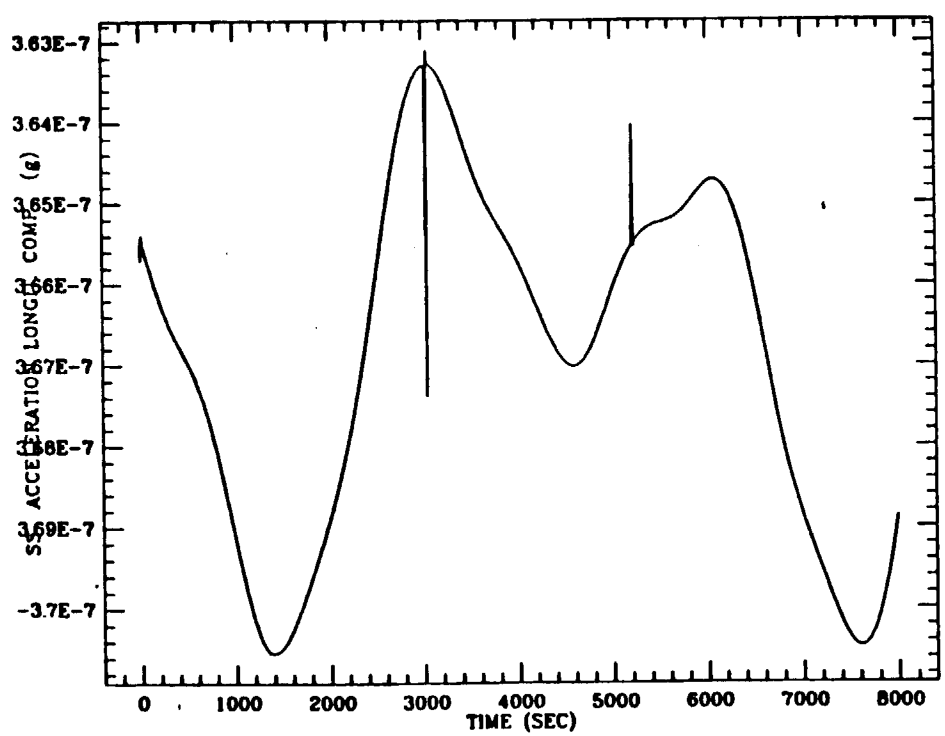
- SYSTEM CHARACTERISTICS
  - $M_1 = 70.4$ kg
  - $M_2 = 200 \times 10^{-3}$ kg
- ALUMINUM TETHER
  - $\ell_1 = 1660$ m
  - $m_T = 79$ kg
  - diameter = 0.005 m
- DAMPER CHARACTERISTICS
  - TUNED
  - $\omega_D = 2.842$ rad/sec
  - $b_d = 562$ N/(m/sec)




TETHER TEMPERATURE (DEG K)
380
370
360
350
340
330
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)


SS TENSION (N)
.72
.718
.716
.714
.712
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)


SS ACCELERATION COMP'S (g)
8E-7
6E-7
4E-7
2E-7
0
-2E-7
-4E-7
Front
Side
Longit.
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)


SS ACCELERATION LONGIT. COMP. (g)
3.63E-7
3.64E-7
3.65E-7
3.66E-7
3.67E-7
3.68E-7
3.69E-7
-3.7E-7
0
1000
2000
3000
4000
5000
6000
7000
8000
TIME (SEC)

STES DYNAMICS: RESULTS

- THE FRONT COMPONENT, PRIMARILY RELATED TO THE AIR DRAG, IS THE LARGEST COMPONENT

- THE LONGITUDINAL COMPONENT AT THE SS CM (1 M FROM THE G-LAB LOCATION) IS SMOOTHER THAN FOR THE DTCS CASE BECAUSE OF THE SHORTER TETHER LENGTH AND LIGHTER END-PLATFORM

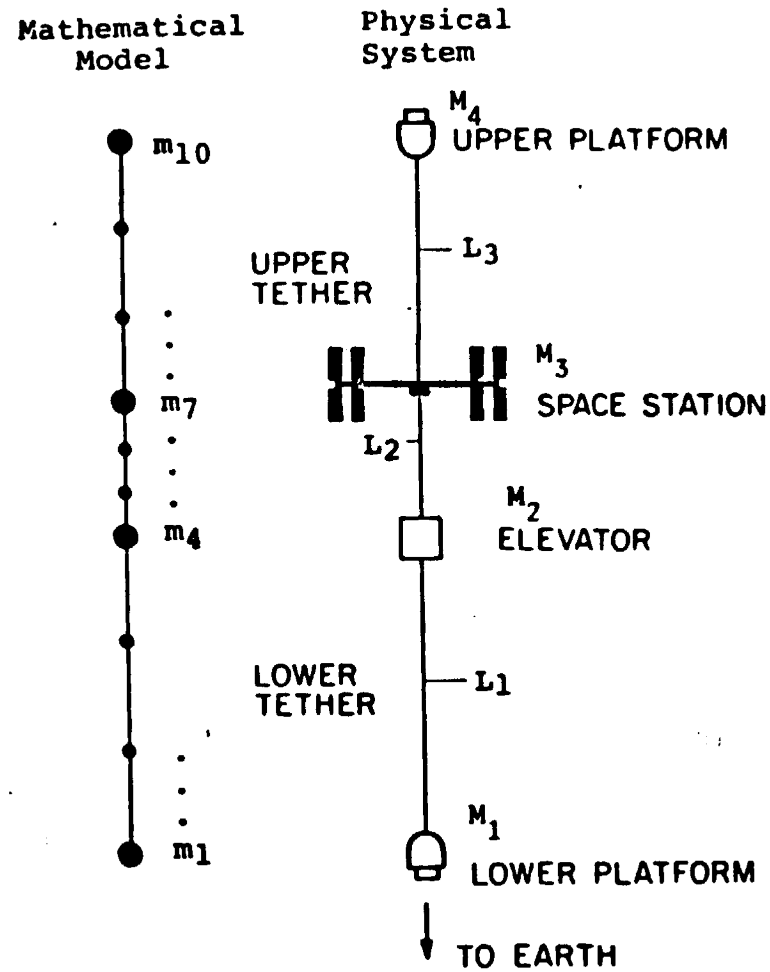
- THE TETHER-RELATED ACCELERATIONS FLUCTUATIONS AROUND THE DC VALUE ON BOARD THE SS ARE OF THE ORDER OF 10^{-8} g

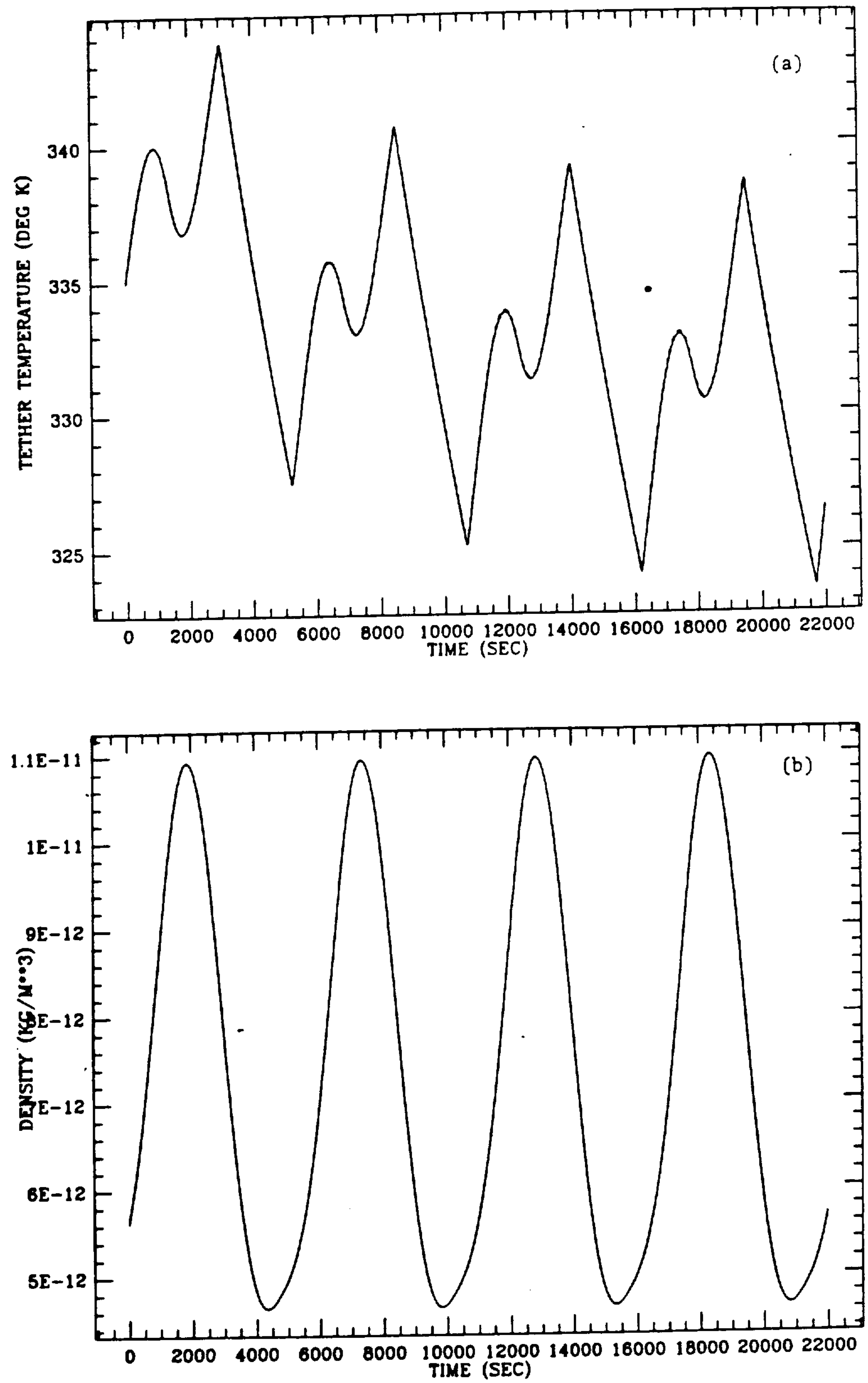
DOUBLE TETHER SYSTEM WITH SPACE ELEVATOR (DTSSE)

- SYSTEM CHARACTERISTICS
  - $M_1 = 2750$ kg
  - $M_2(EL) = 2250$ kg
  - $M_3(SS) = 200 \times 10^3$ kg
  - $M_4 = 3460$

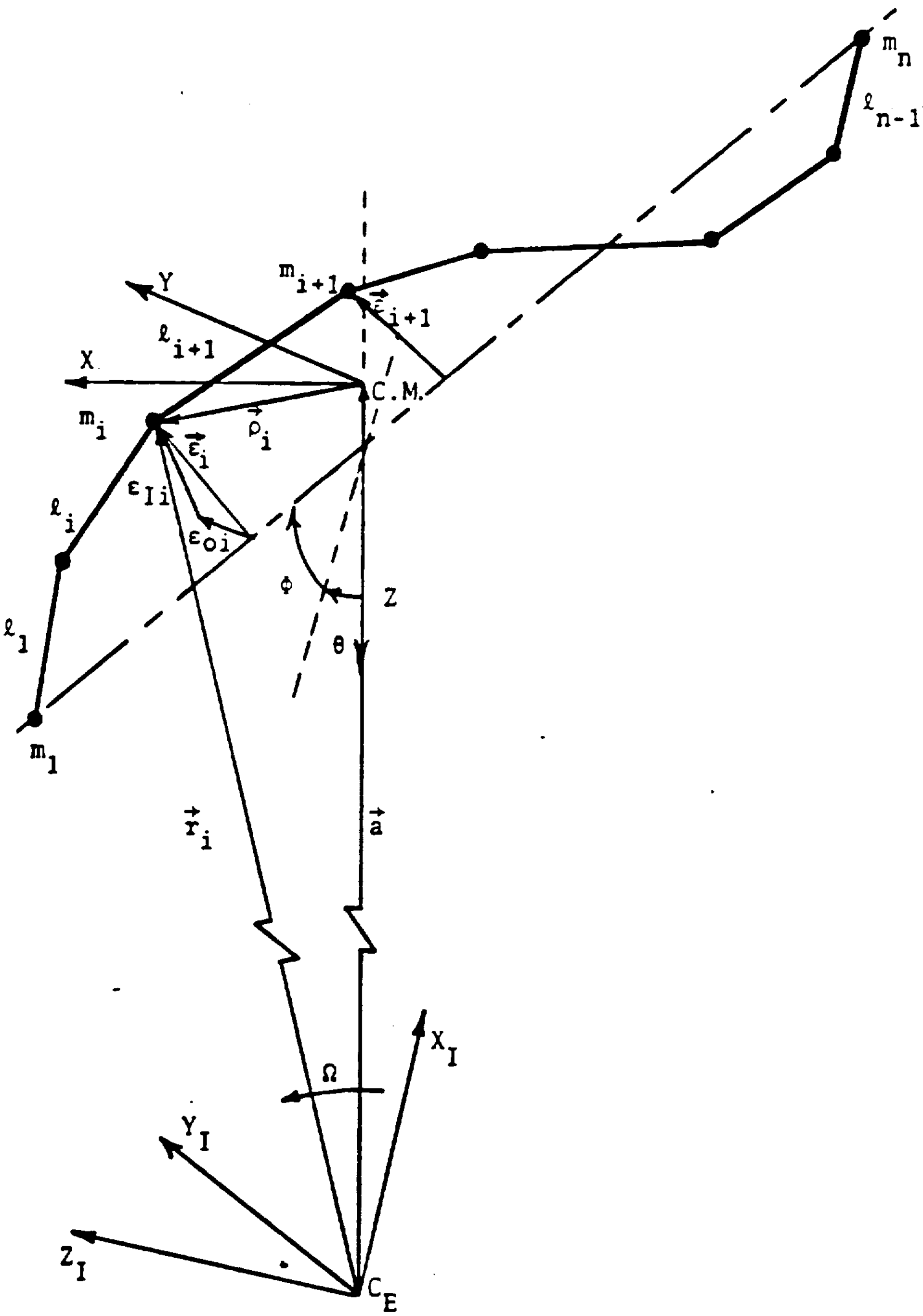
- ALUMINUM TETHERS
  - $\ell_1 = 4060$ m; $m_{T1} = 774$ kg; diam. = 9 mm
  - $\ell_2 = 1640$ m; $m_{T2} = 313$ kg; diam. = 9 mm
  - $\ell_3 = 4977$ m; $m_{T3} = 949$ kg; diam. = 9 mm

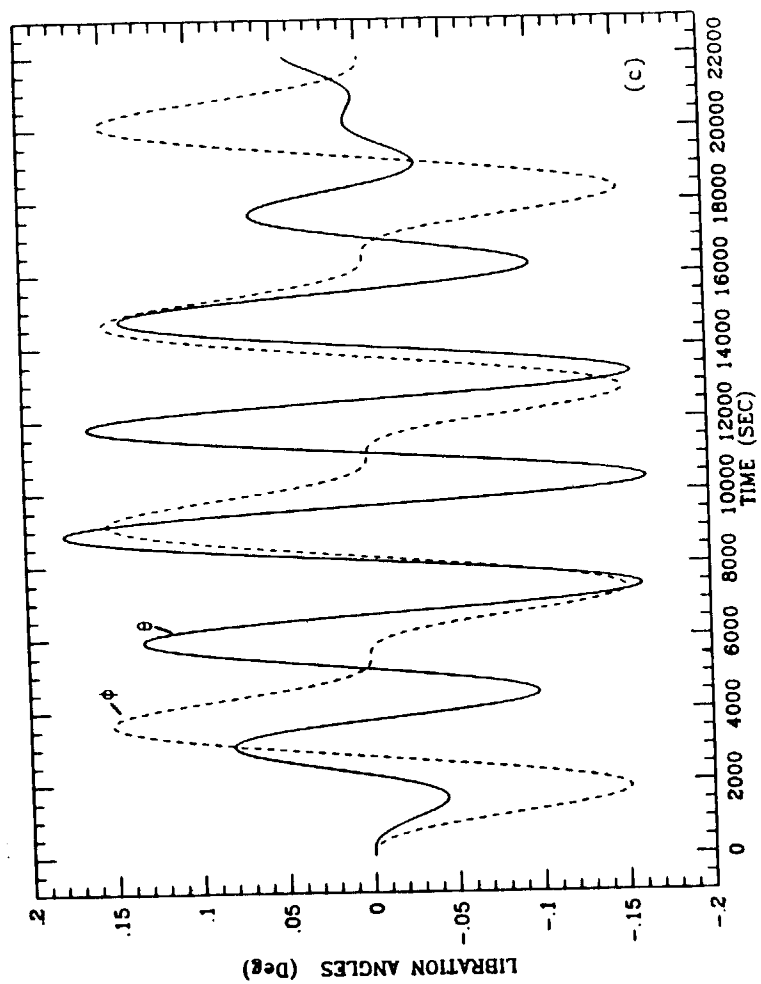
- DAMPER CHARACTERISTICS
  - TUNED
  - $\omega_{D1} = 0.5395$ rad/s; $b_{D1} = 3920$ N/(m/sec)
  - $\omega_{D2} = 1.3611$ rad/s; $b_{D2} = 3847$ N/(m/sec)
  - $\omega_{D3} = 0.4991$ rad/s; $b_{D3} = 3457$ N/(m/sec)

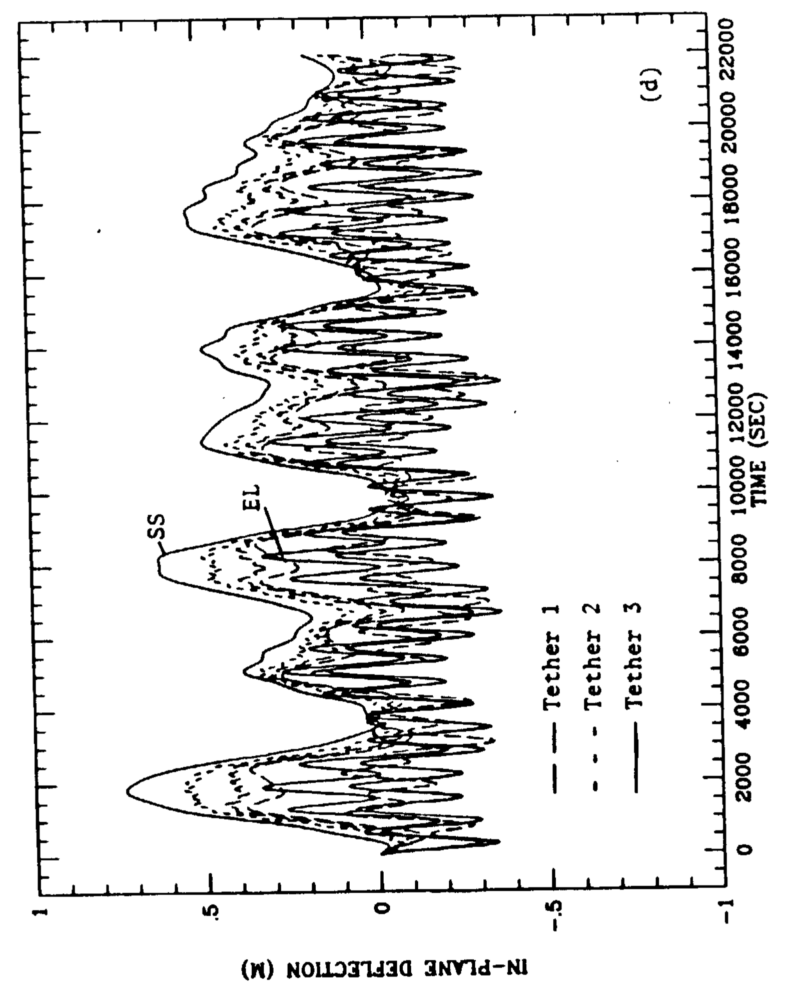


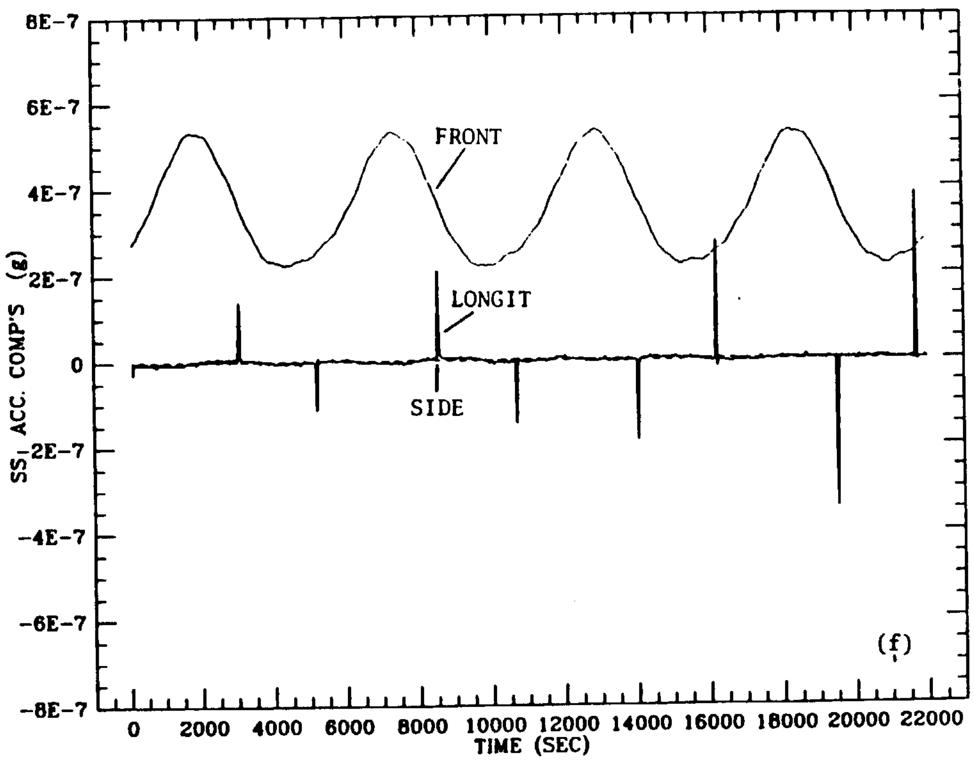

(a)
TETHER TEMPERATURE (DEG K)
340
335
330
325
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000
TIME (SEC)
(b)
DENSITY (KG/M**3)
1.1E-11
1E-11
9E-12
6E-12
5E-12
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000
TIME (SEC)

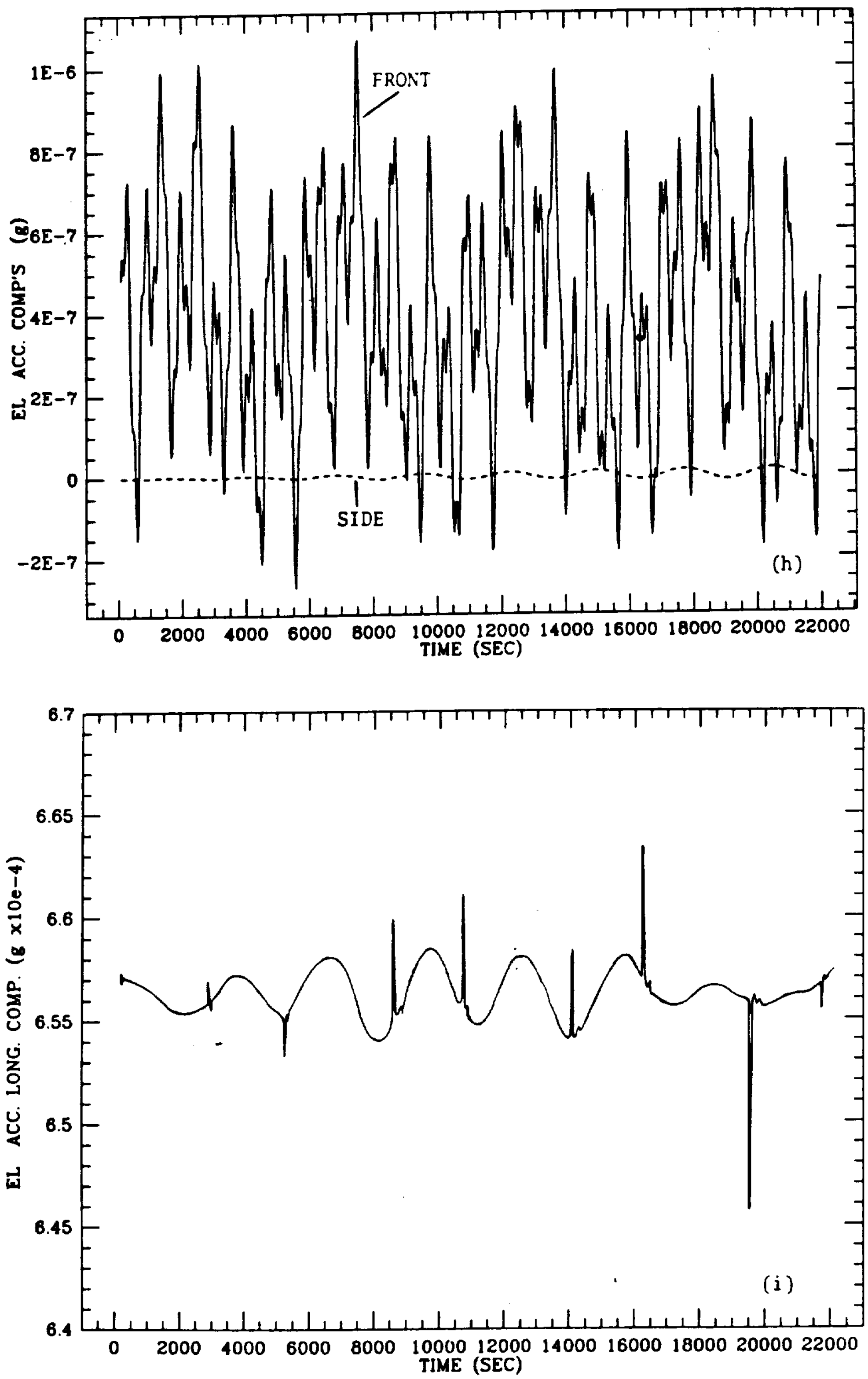
- Reference Frames




LIBRATION ANGLES (Deg)
TIME (SEC)
(c)
θ
φ


IN-PLANE DEFLECTION (M)
TIME (SEC)
(d)
Tether 1
Tether 2
Tether 3
SS
EL


8E-7
6E-7
4E-7
2E-7
0
-2E-7
-4E-7
-6E-7
-8E-7
SS ACC. COMP'S (g)
FRONT
LONGIT
SIDE
(f)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
TIME (SEC)



EL ACC. COMP'S (g)
1E-6
8E-7
6E-7
4E-7
2E-7
0
-2E-7
FRONT
SIDE
(h)
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000
TIME (SEC)
EL ACC. LONG. COMP. (g x10e-4)
6.7
6.65
6.6
6.55
6.5
6.45
6.4
(i)
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000
TIME (SEC)

DTSSE DYNAMICS: RESULTS

- THE MAXIMUM VALUES OF THE ACCELERATION FLUCTUATIONS ON BOARD THE SS ARE ALWAYS BELOW 10^{-6} g, THE THERMAL SHOCKS PRODUCE THE LARGEST TETHER-RELATED ACCELERATION NOISE

- THE FRONT COMPONENT ON BOARD THE ELEVATOR IS AFFECTED PRIMARILY BY AIR DRAG

- THE LONGITUDINAL COMPONENT ON BOARD THE ELEVATOR EXHIBITS A DC COMPONENT DUE TO THE 1660 M–OFFSET FROM THE ORBITAL CENTER

- THE LOW FREQUENCY FLUCTUATION OF THE LONGITUDINAL COMPONENT ON BOARD THE ELEVATOR IS RELATED TO J_2

- THE MAXIMUM FLUCTUATION OF THE LONGITUDINAL COMPONENT ON BOARD THE ELEVATOR, WITH RESPECT TO THE DC VALUE, IS AROUND 10^{-5} g

CONCLUSIONS

- ALL THE THREE CONFIGURATIONS PROPOSED MEET THE 10^{-5} g MICROGRAVITY REQUIREMENT FOR THE ACCELERATION ON BOARD THE STATION IF LONGITUDINAL DAMPERS, TUNED TO THE BOBBING FREQUENCY OF THE ASSOCIATED TETHER, ARE ADDED

- THE TETHER-RELATED NOISE ON BOARD THE STATION IS PRIMARILY GENERATED BY THERMAL SHOCKS.

- THE AIR DRAG RESPONSIBLE OF THE FRONT COMPONENT OF THE ACCELERATION, IS MAINLY RELATED TO THE FRONTAL AREA OF THE STATION. THE CONTRIBUTIONS OF THE TETHER'S CROSS SECTIONS IS MARGINAL

- FOR A DOUBLE TETHERED SYSTEM WITH OR WITHOUT SPACE ELEVATOR THE MAXIMUM ACCELERATION LEVEL ON BOARD THE SS IS LESS THAN 10^{-6} g. THE PERFORMANCE OF A SINGLE TETHER SYSTEM IS EVEN BETTER.

- THE G-QUALITY ON BOARD THE ELEVATOR (DTSSE) IS COMPARABLE TO THE G-QUALITY (ACCELERATIONS FLUCTUATIONS) OF THE MICRO-G LAB ATTACHED TO THE SS

TETHERED DYNAMIC ABSORBER

- SINCE MICROGRAVITY EXPERIMENTS ARE MOST SENSITIVE TO LOW-FREQUENCY DISTURBANCES, THE LOW-FREQUENCY STRUCTURAL MODES ($\sim 10^{-1}$ HZ) OF THE STATION ARE POTENTIALLY A MAJOR SOURCE OF NOISE

- TETHERS HAVE THE CAPABILITY IN DAMPING OUT THE UNDESIRED OSCILLATIONS BY TUNING THE TETHER BOBBING FREQUENCY TO THE PERTURBATIVE FREQUENCY

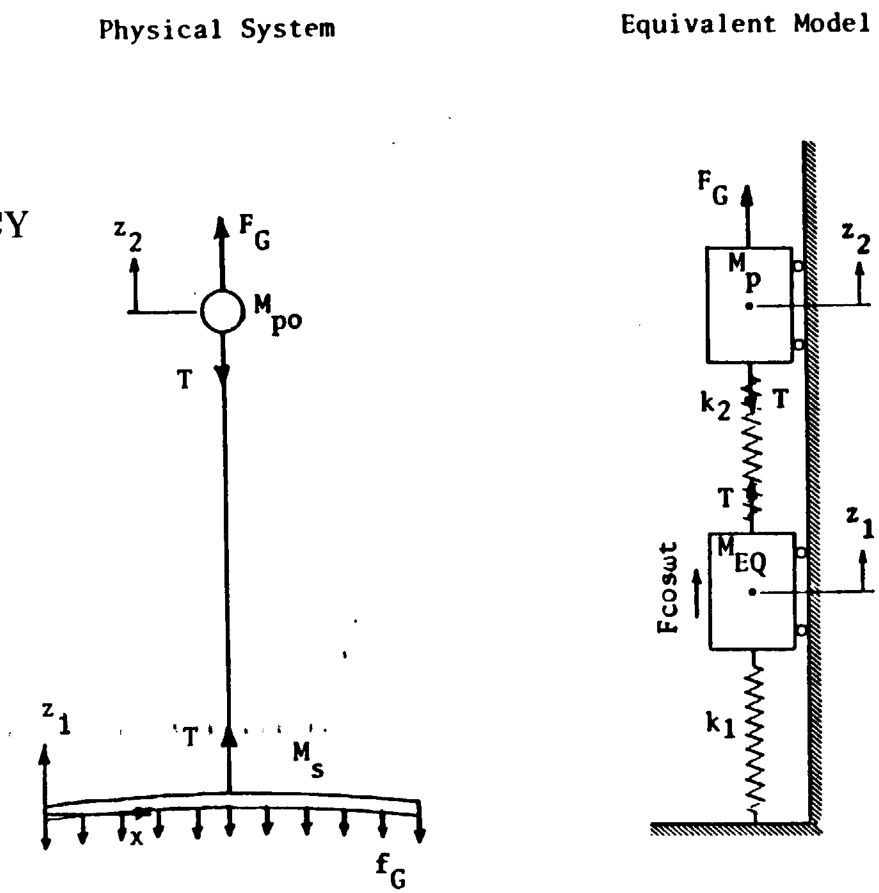
- IN THE FOLLOWING IT IS SHOWN HOW A TETHER SYSTEM CAN DAMP OUT THE FIRST FLEXURAL MODE OF THE STATION

TETHERED DYNAMIC ABSORBER

- THE SYSTEM IS AMENABLE TO AN ANALYTICAL SOLUTION SINCE THE PHYSICAL SYSTEM CAN BE REDUCED TO A CLASSIC TWO MASSES – TWO SPRING OSCILLATOR
  - THE EQUIVALENT MASS M_{EQ} OF THE POINT MASS SPACE STATION, COMPUTED BY ASSUMING SAME ENERGY FREQUENCY AND AMPLITUDE, IS FOUND TO BE EQUAL TO 0.757 M_S
  - THE SPRING CONSTANTS ARE:

$$k_1 = M_{EQ}\omega_1^2 = 0.757\ M_S\omega_1^2$$
$$k_2 = m_p\omega_2^2$$

- ONCE THAT THE TETHER (e.g. ω_2) IS TUNED TO THE FREQUENCY OF THE PERTURBATIVE FORCE THE OSCILLATION OF THE STATION CEASES



TETHERED DYNAMIC ABSORBER

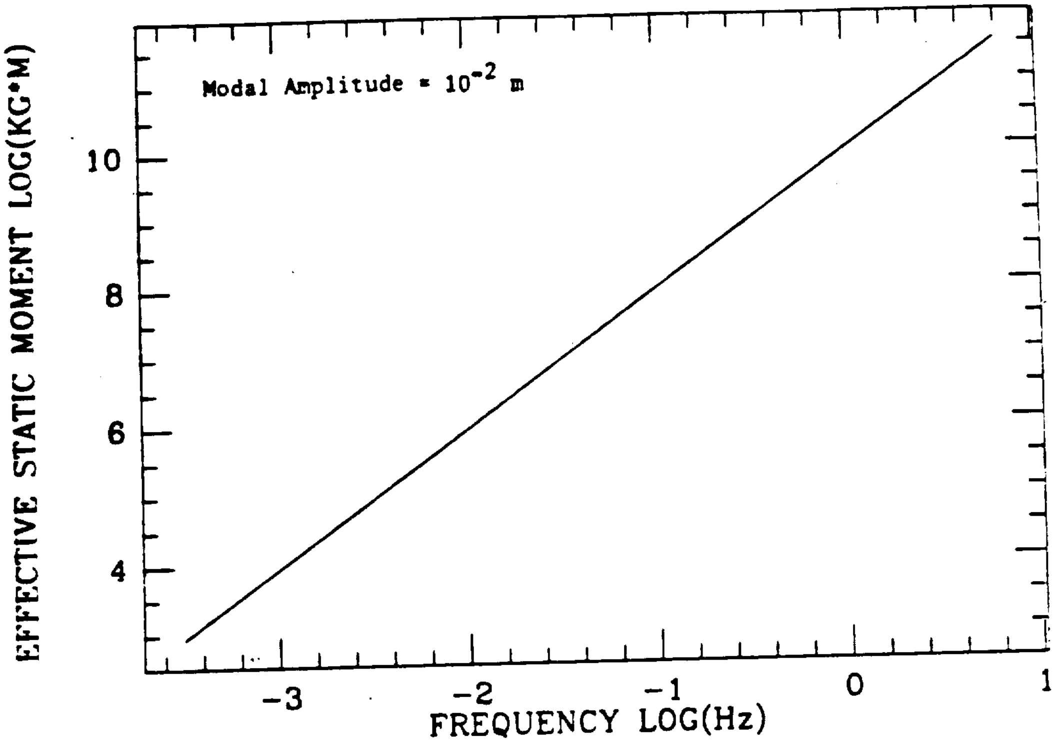
- IN PRINCIPLE A TETHER SYSTEM CAN ATTENUATE THE FIRST FLEXURAL MODE OF THE STATION

- IN REALITY THE AVOIDANCE OF TETHER SLACKNESS POSES A STRONG CONSTRAINT TO THE DESIGN OF SUCH DEVICES, SINCE THE INERTIA FORCES MUST BE ALWAYS BALANCED BY THE TETHER TENSION DURING THE DAMPING CYCLE

- SINCE THE MINIMUM STATIC MOMENT IS INVERSELY PROPORTIONAL TO THE SQUARE OF THE FREQUENCY, QUITE MASSIVE TETHERED SYSTEMS MUST BE USED AT FREQUENCIES AROUND 10^{-1} Hz

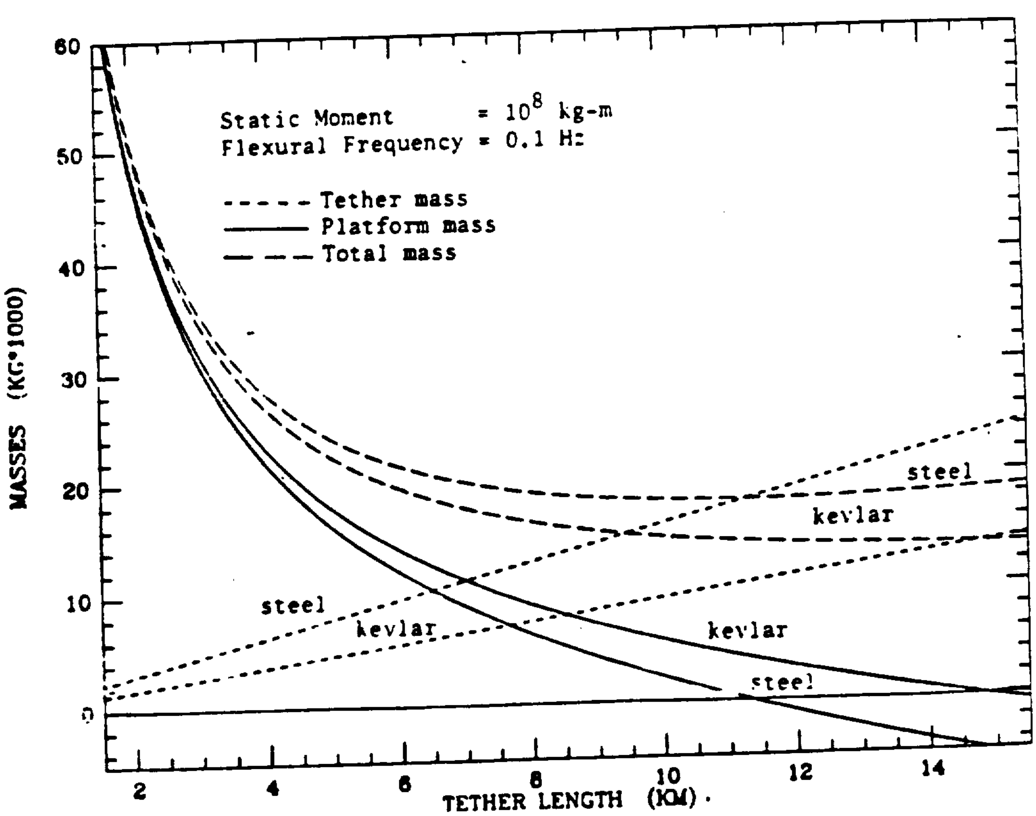
- IN ORDER TO NEUTRALIZE THE CM SHIFT, THE TETHER DYNAMIC ABSORBER MUST BE USED ONLY IN A DTCS-LIKE CONFIGURATION. THE OTHER TETHER SEGMENT MUST BE DETUNED (A LOWER BOBBING FREQUENCY IS RECOMMENDED)

- FOR FLEXURAL FREQUENCY $f = 0.1$ Hz
  - TETHER LENGTH = 10 KM
  - TETHER DIA = 28.5 MM KEVLAR
  - TETHER DIA = 15.8 MM STEEL



– 28.5 MM–DIAMETER KEVLAR TETHER

– 15.8 MM–DIAMETER STEEL TETHER



CONCLUSIONS

- A TETHERED DYNAMIC ABSORBER CAN ABATE THE STATION'S FIRST FLEXURAL MODE
    - IN ORDER TO AVOID TETHER SLACKENING, THE SYSTEM MUST BE QUITE MASSIVE
    - A DTSSE CAN POTENTIALLY PROVIDE THIS CAPABILITY IF APPROPRIATELY DESIGNED

VARIABLE GRAVITY LABORATORY

CONTROL STRATEGIES AND ACCELERATION LEVELS

SUMMARY

- DYNAMIC RESPONSE OF VGL STATIONED AT ORBITAL CENTER
- CONTROL LAWS FOR CRAWLING MANEUVERS
- TRANSIENT DYNAMICS DURING CRAWLING MANEUVERS
  - –SHORT, MEDIUM AND LONG DISTANCE MANEUVERS
- OSCILLATION DAMPERS
  - –LIBRATIONAL/LATERAL DAMPER
  - –DETUNING OF LONGITUDINAL DAMPERS
- FAST CRAWLING MANEUVERS
- STATION-RELATED DISTURBANCES/PROPAGATION ALONG TETHER
- VGL ATTITUDE DYNAMICS

VARIABLE GRAVITY LABORATORY SYSTEM

- SYSTEM CHARACTERISTICS

  $M_1 = 2200$ KG

  $M_2(EL) = 2000$ KG

  $M_3(SS) = 204.5 \times 10^3$ KG

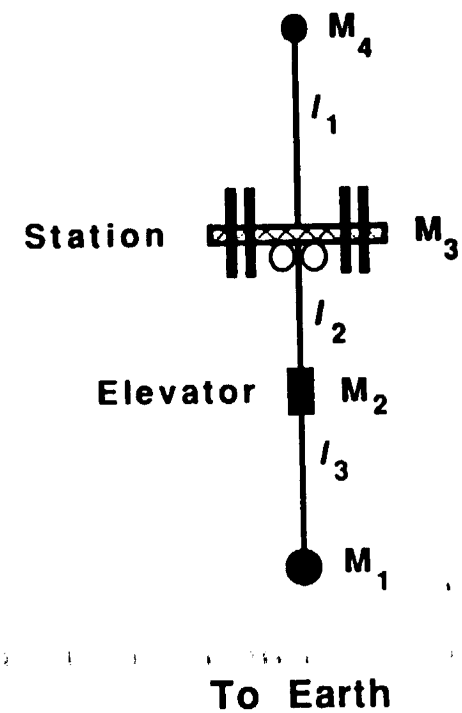
- KEVLAR TETHER

  ℓ (LENGTH) = 10.5 KM

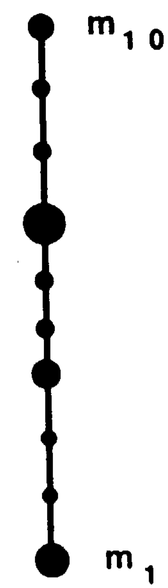
  DIA = 10 MM

  m_T (TETHER MASS) = 1187 KG

DTSSE Physical model



Discretization

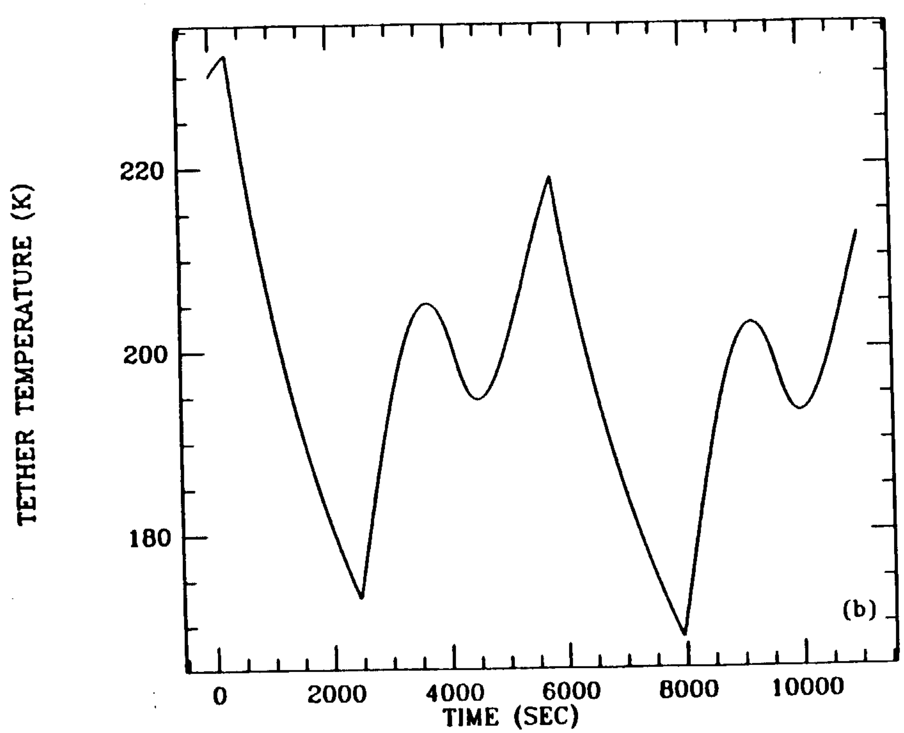


DYNAMIC RESPONSE WITH ELEVATOR AT ORBITAL CENTER

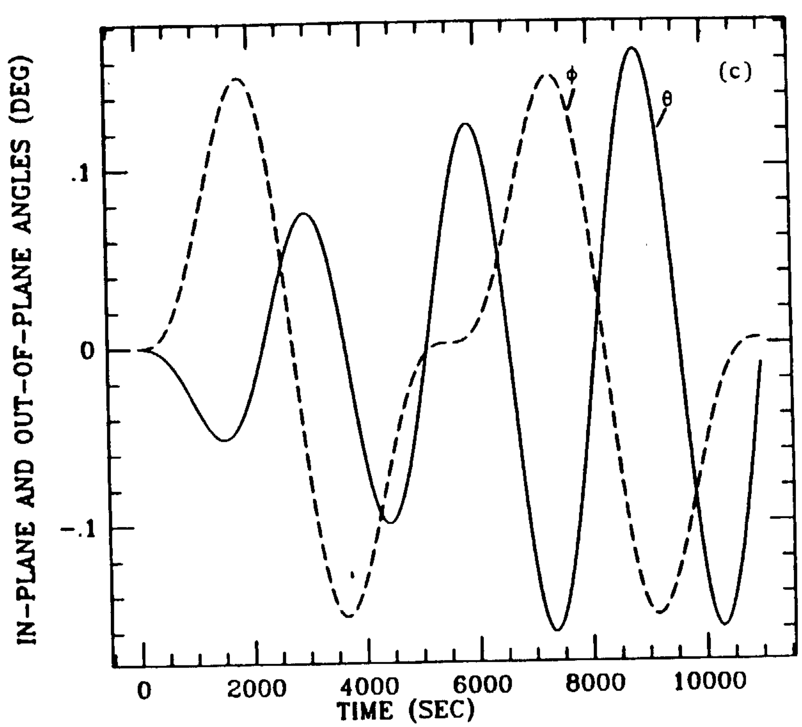
- ORBITAL CENTER (CO) = POINT WHERE GRAVITY AND CENTRIFUGAL FORCES BALANCE OUT (IN VGL, CO IS 1 M OFF CM)

- ASSUMPTIONS
  - –VISCOUS TETHER MATERIAL DAMPING

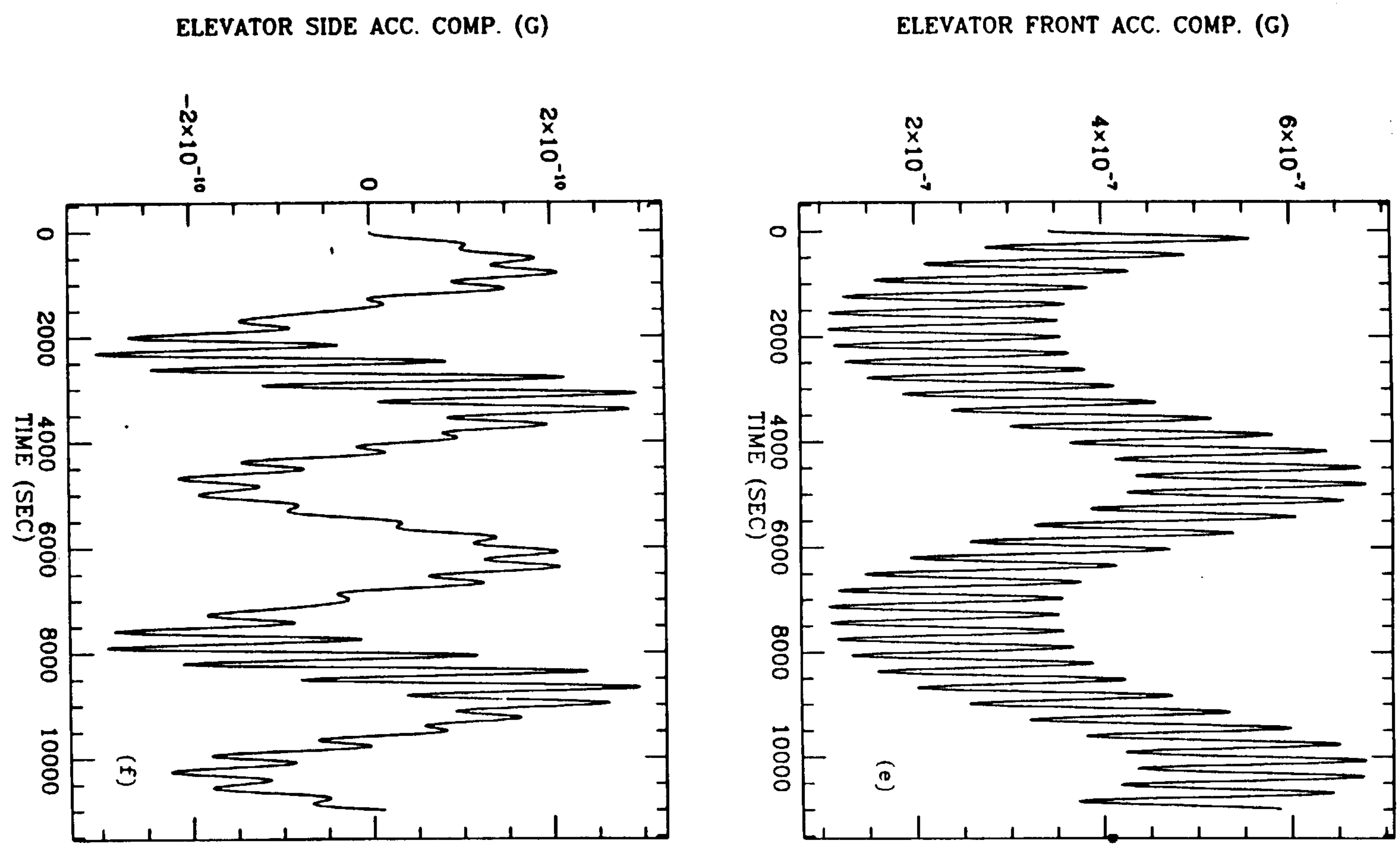
    FIRST MODE DAMPING RATIO = 2%
  - –INITIAL TETHER TEMPERATURE = 230°K (CLOSE TO EQUILIBRIUM TEMP)
  - –SUN AT SUMMER SOLSTICE
  - –FIXED ELEVATOR
  - –SYSTEM INITIALLY ALIGNED WITH LOCAL VERTICAL
  - –LONGITUDINAL DAMPERS ACTIVATED

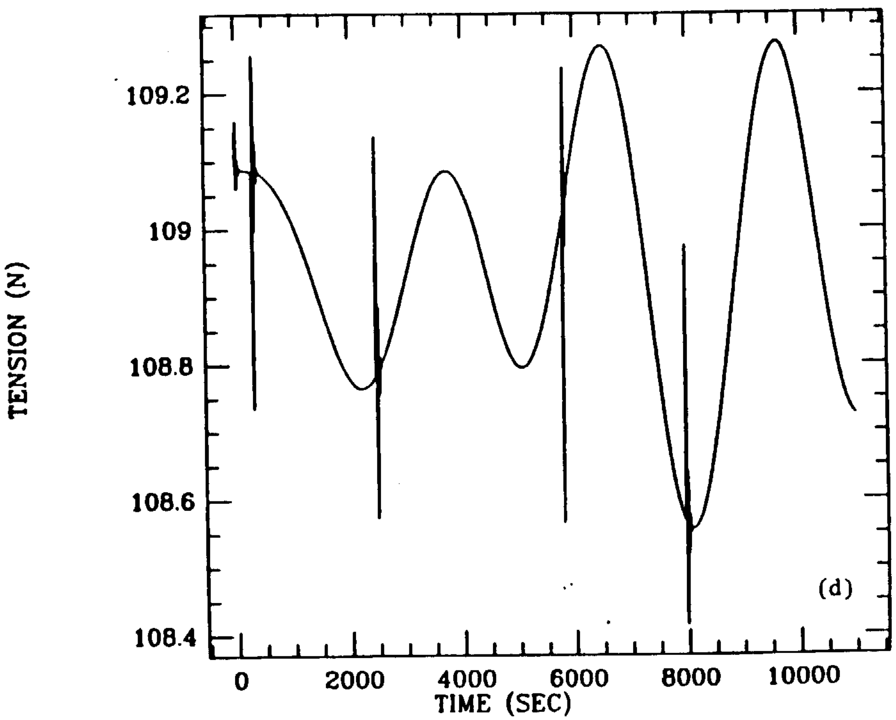


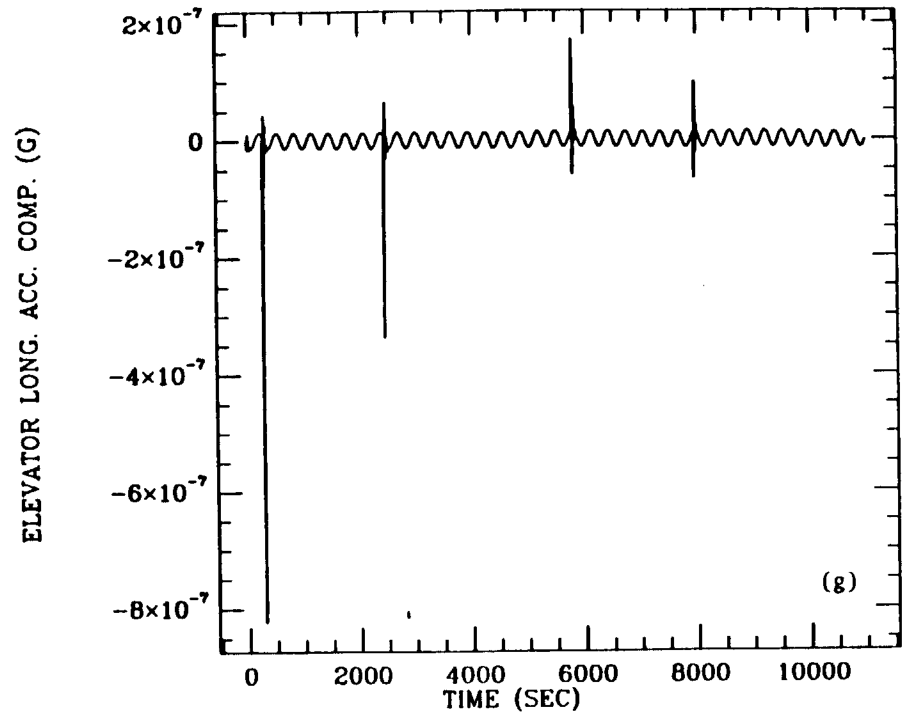
TETHER TEMPERATURE (K)
220
200
180
0
2000
4000
6000
8000
10000
TIME (SEC)
(b)



IN-PLANE AND OUT-OF-PLANE ANGLES (DEG)
.1
0
-.1
0
2000
4000
6000
8000
10000
TIME (SEC)
(c)
ϕ
θ


ELEVATOR SIDE ACC. COMP. (G)
-2×10^-10
0
2×10^-10
(f)
0
2000
4000
6000
8000
10000
TIME (SEC)
ELEVATOR FRONT ACC. COMP. (G)
2×10^-7
4×10^-7
6×10^-7
(e)
0
2000
4000
6000
8000
10000
TIME (SEC)





- MAXIMUM ACCELERATION FLUCTUATIONS LESS THAN 10^{-6} G

CONTROL LAWS FOR CRAWLING MANEUVERS

- MIRROR IMAGE MOTION CONTROL LAW (MIMCL)

DEVELOPED BY SAO, NASA/MSFC AND TRI-STATE UNIVERSITY

—ACCELERATION $t < t_A$

$$\Delta\ell = \Delta\ell'[\tanh(\alpha t)]^{\gamma}$$

—CONSTANT VELOCITY $t_A \leq t \leq t_B$

$$\Delta\ell = \Delta\ell'[\tanh(\alpha t_A)]^{\gamma} + \Delta\ell'' \ \frac{t - t_A}{t_B - t_A}$$

—DECELERATION $t_B < t \leq t_T$

$$\Delta\ell = \Delta\ell_T - \Delta\ell'\left\{\tanh[\alpha(t_T - t)]\right\}^{\gamma}$$

$\Delta\ell''$ = distance travelled at constant velocity; $\Delta\ell_T$ = total travelled distance

$\Delta\ell'$ = length of the hyperbolic tangent phases

- CONTROL LAW CHARACTERISTICS
  - –LOW PEAK ACCELERATIONS
  - –SMOOTH STARTS AND STOPS
  - –RELATIVELY FAST MANEUVERS
  - –LOW VALUES OF MAXIMUM VELOCITIES
  - –PERFORMANCE CAN BE ADJUSTED BY VARYING, α, Y, and γ
- MOTION-INDUCED-ACCELERATION MINIMIZED BY

$$Y = 66.4\%, \qquad \gamma = 5$$

- α = RATE PARAMETER ($1/\alpha$ = TIME CONSTANT)
- γ = SHAPE PARAMETER
- Y = DISTANCE TRAVELLED AT CONSTANT SPEED

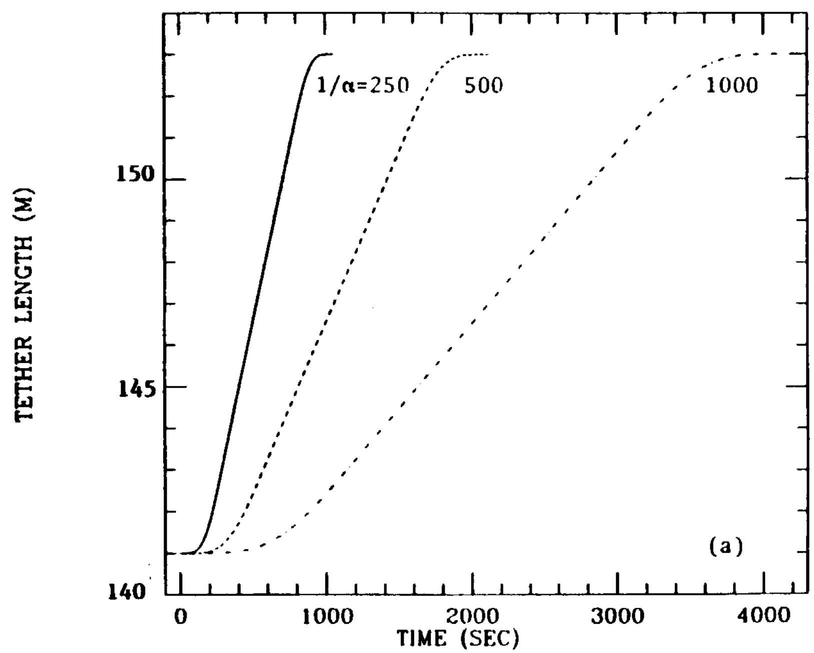
- STEADY-STATE ACCELERATION LEVELS REQUIRED FOR LOW-GRAVITY EXPERIMENTS

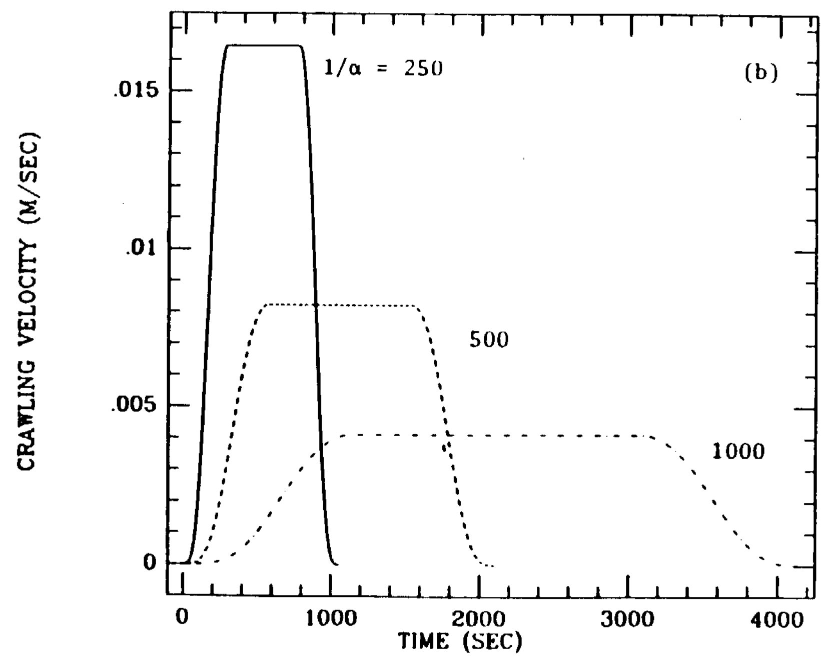
Table 1. Gravity Levels On-Board VGL and SS vs. the VGL-SS Distance

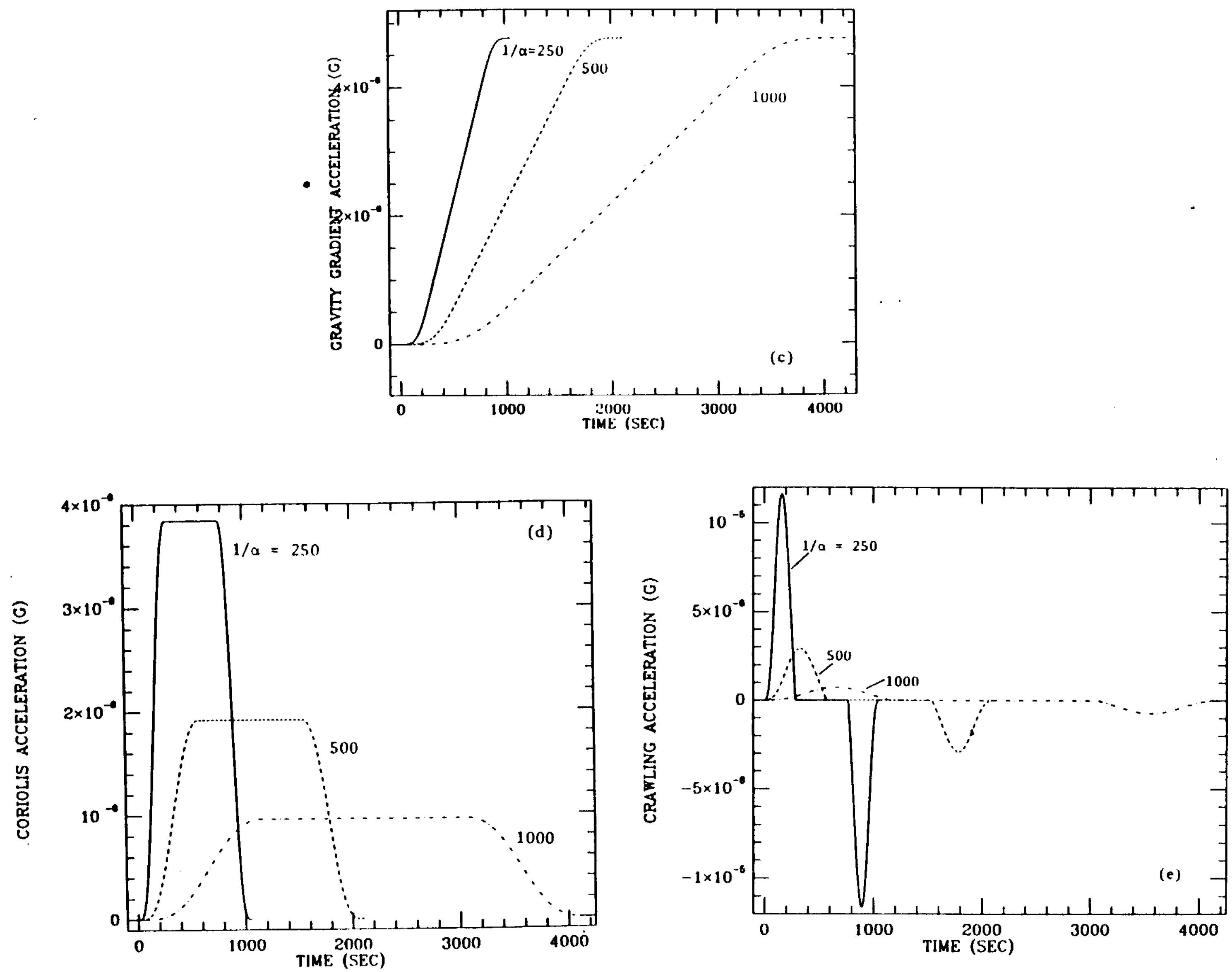
$\lvert a_{VGL} \rvert$(g)	$\lvert a_{SS} \rvert$(g)	ℓ_2(m)
0	5.64×10^{-5}	141
5×10^{-6}	5.65×10^{-5}	154
10^{-5}	5.65×10^{-5}	167
5×10^{-5}	5.69×10^{-5}	268
10^{-4}	5.74×10^{-5}	394
5×10^{-4}	6.12×10^{-5}	1404
10^{-3}	6.60×10^{-5}	2667
4×10^{-3}	9.49×10^{-5}	10242

- CONTROL LAW PERFORMANCE (SHORT LENGTH MANEUVER)

—CRAWLING FROM 141 M (0 G) TO 153 M (5×10^{-6} G) OFF STATION



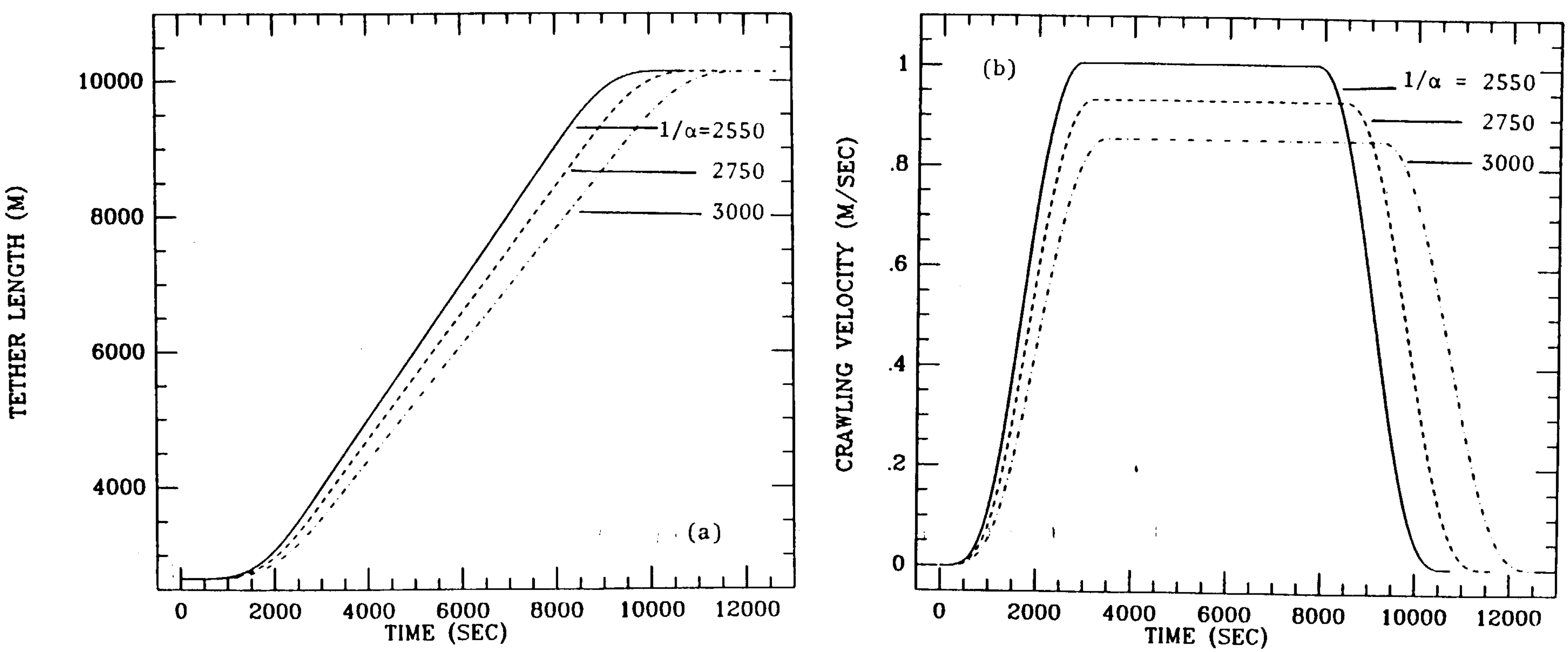


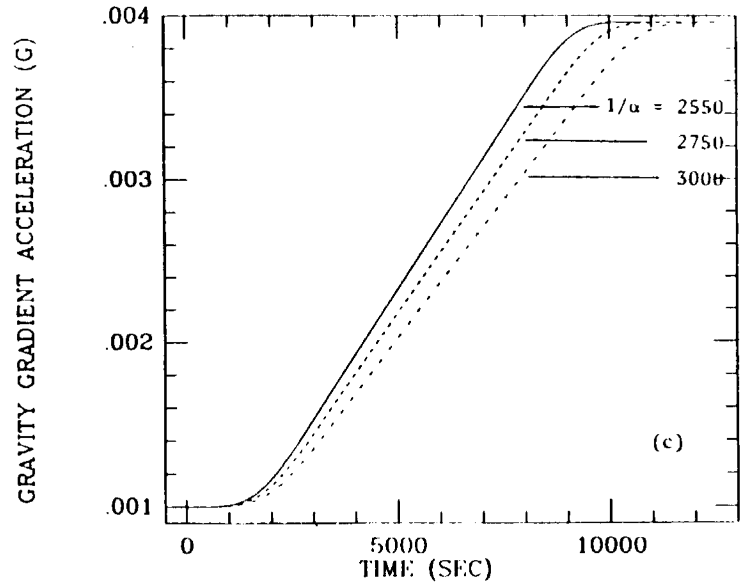


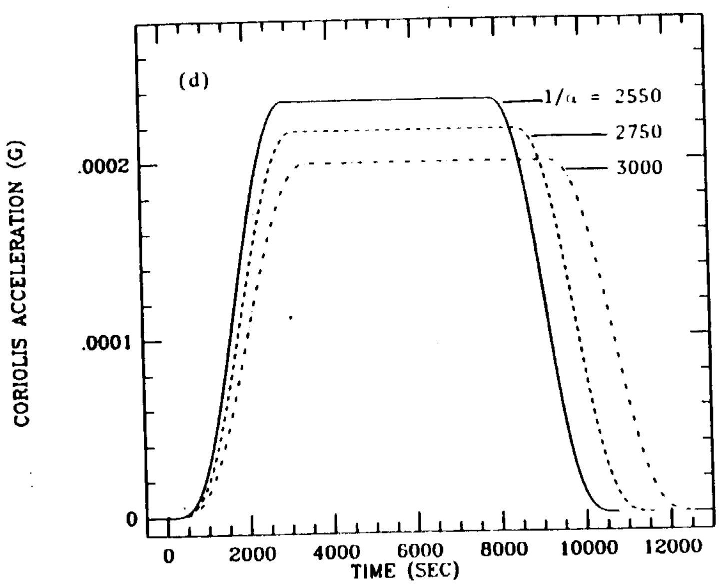
- $1/\alpha$ = 500 S PROVIDES A REASONABLY FAST MANEUVER AND LOW ACCELERATIONS

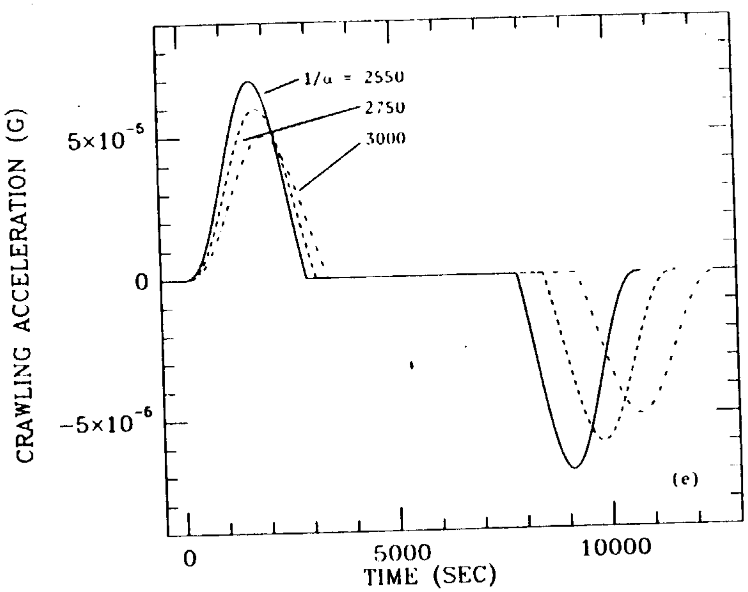
- CONTROL LAW PERFORMANCE (LONG DISTANCE MANEUVER)

—CRAWLING FROM 2667 M (10^{-3} G) TO 10,242 M (4×10^{-3} G) OFF STATION





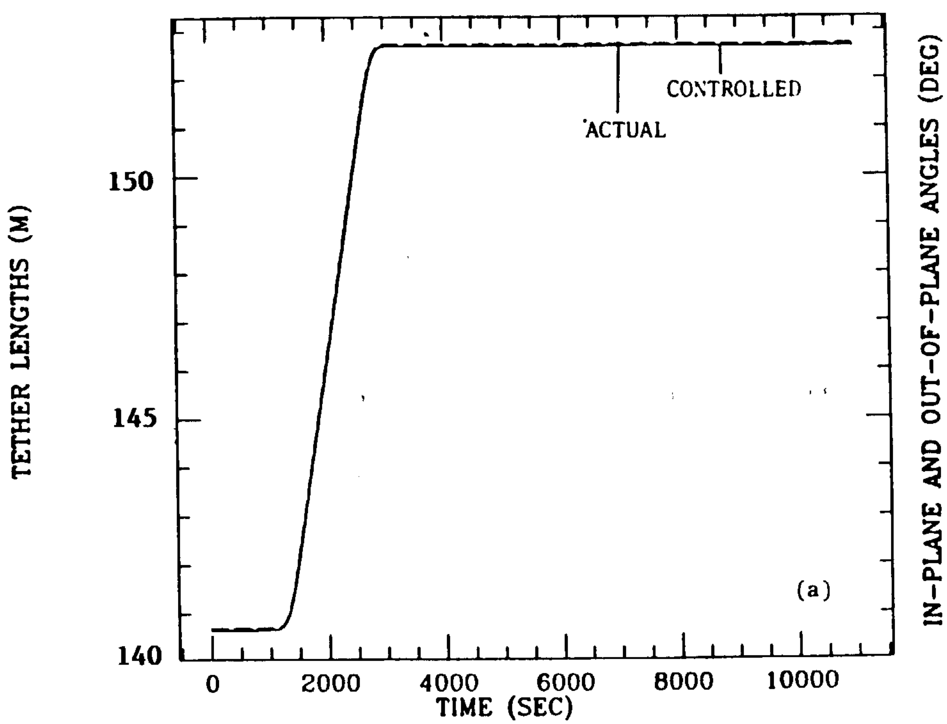


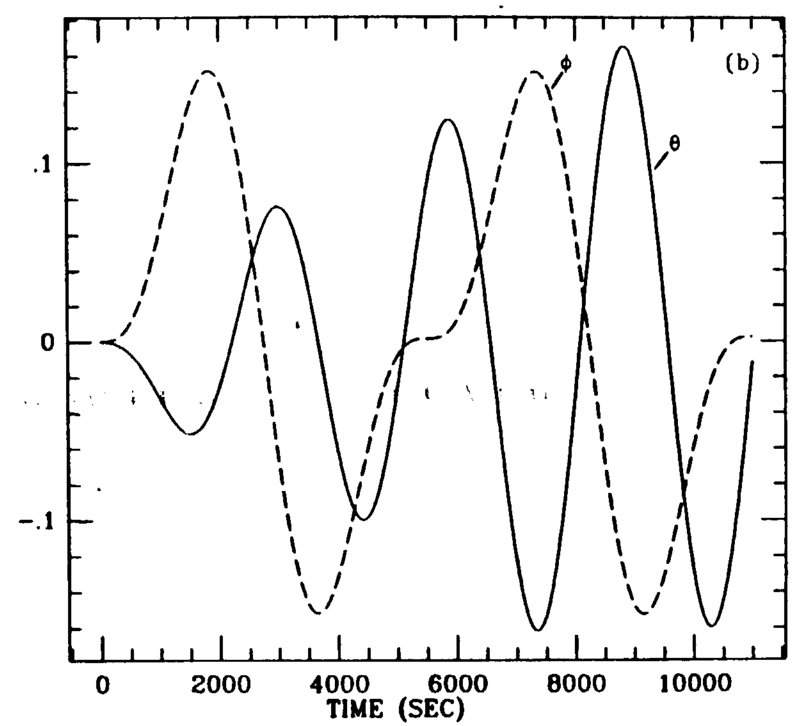


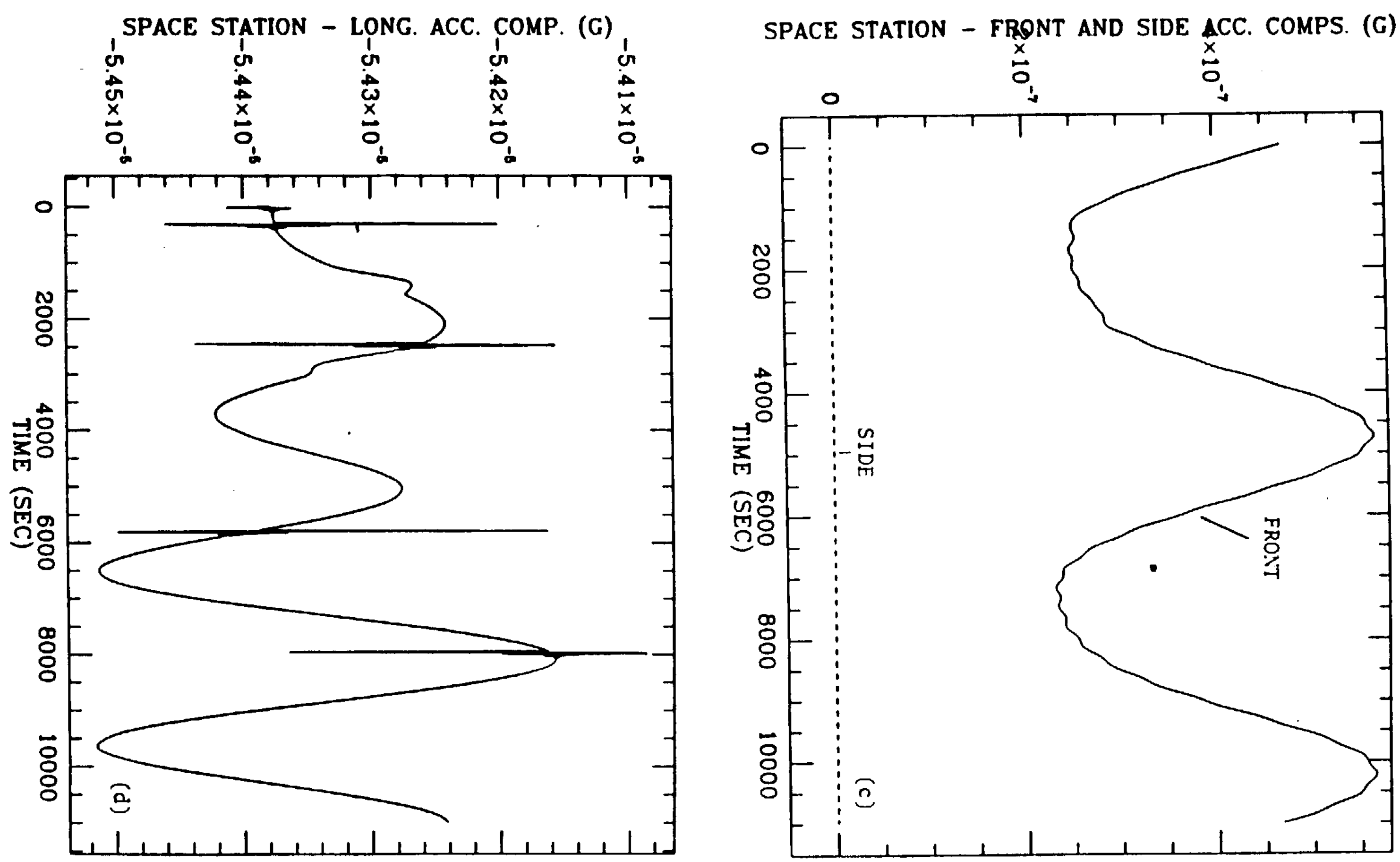
- $1/\alpha > 2550$ IN ORDER NOT TO EXCEED THE MAXIMUM CRAWLING VELOCITY OF THE ELEVATOR = 1 M/S

TRANSIENT DYNAMICS DURING CRAWLING MANEUVERS

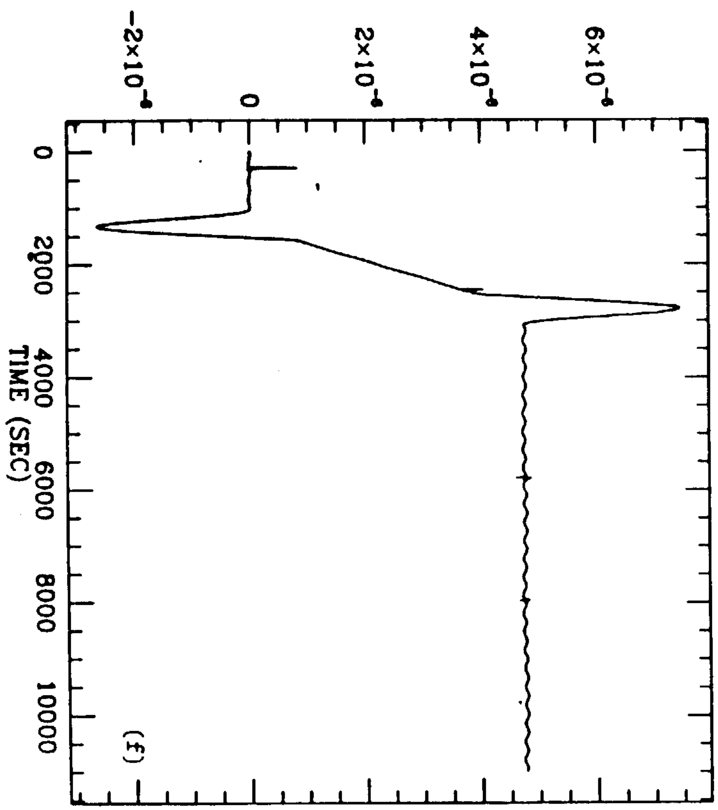
- DYNAMIC RESPONSE OF SHORT DISTANCE CRAWLING MANEUVERS
  - —141 M $\rightarrow$ 153 M FROM 0 G TO 5×10^{-6} G
  - —ONLY LONGITUDINAL DAMPERS ACTIVATED
  - —$1/\alpha$ = 500 S



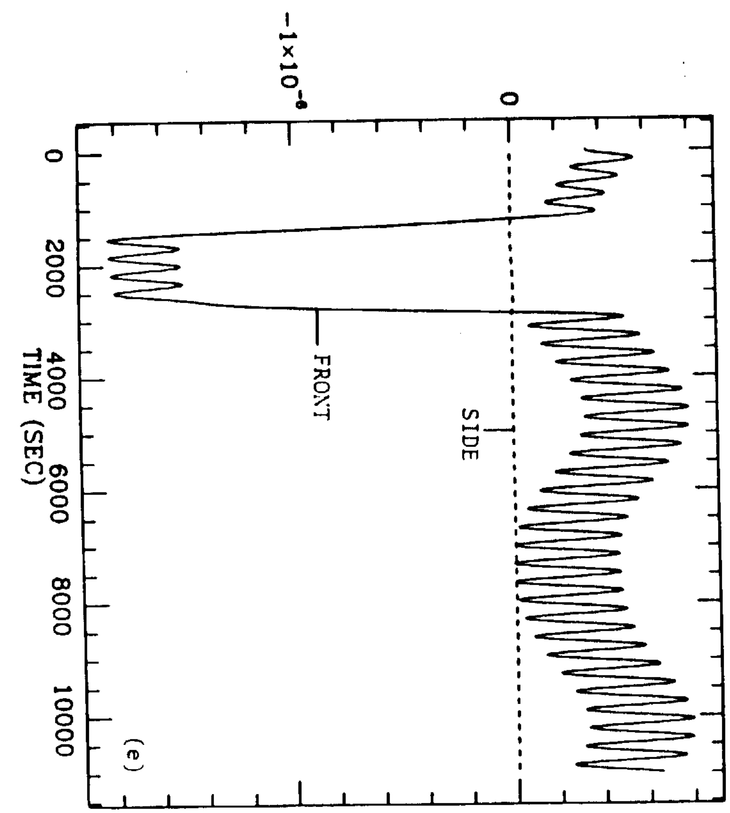



SPACE STATION - LONG. ACC. COMP. (G)
-5.45×10^{-6}
-5.44×10^{-6}
-5.43×10^{-6}
-5.42×10^{-6}
-5.41×10^{-6}
(d)
0
2000
4000
6000
8000
10000
TIME (SEC)
SPACE STATION - FRONT AND SIDE ACC. COMPS. (G)
0
2×10^{-7}
4×10^{-7}
SIDE
FRONT
(c)
0
2000
4000
6000
8000
10000
TIME (SEC)

VGL – LONG. ACC. COMP. (G)



VGL – FRONT AND SIDE ACC. COMPS. (G)

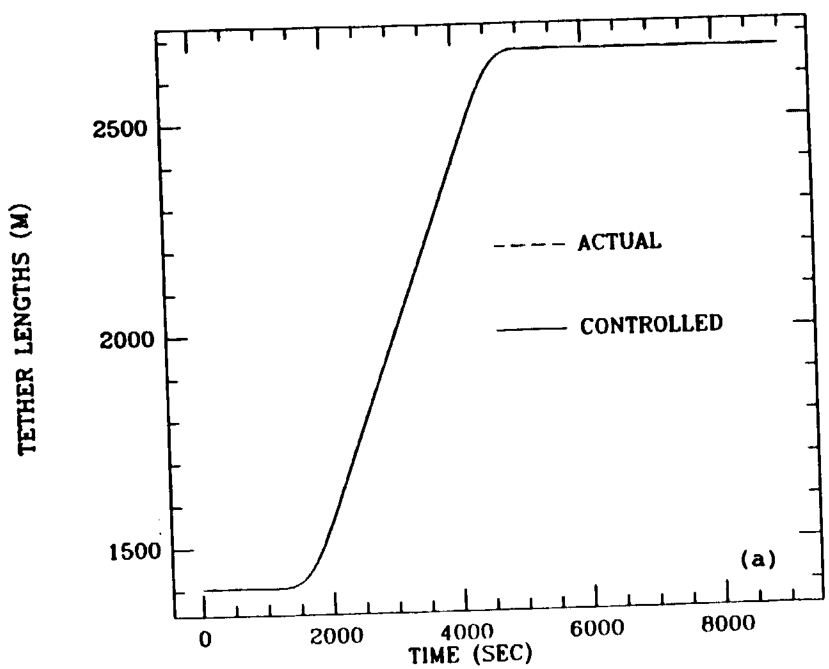


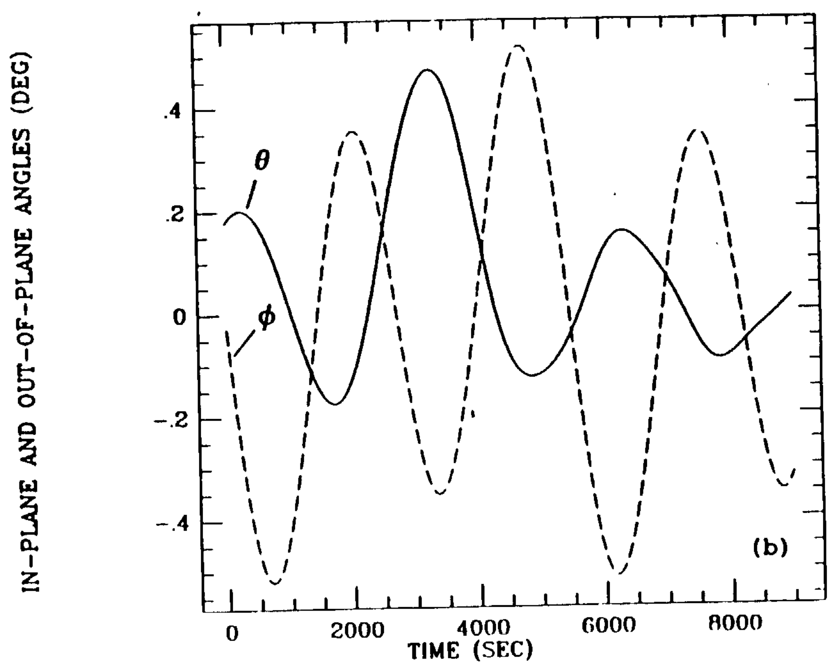
- DYNAMIC RESPONSE OF MEDIUM DISTANCE MANEUVERS

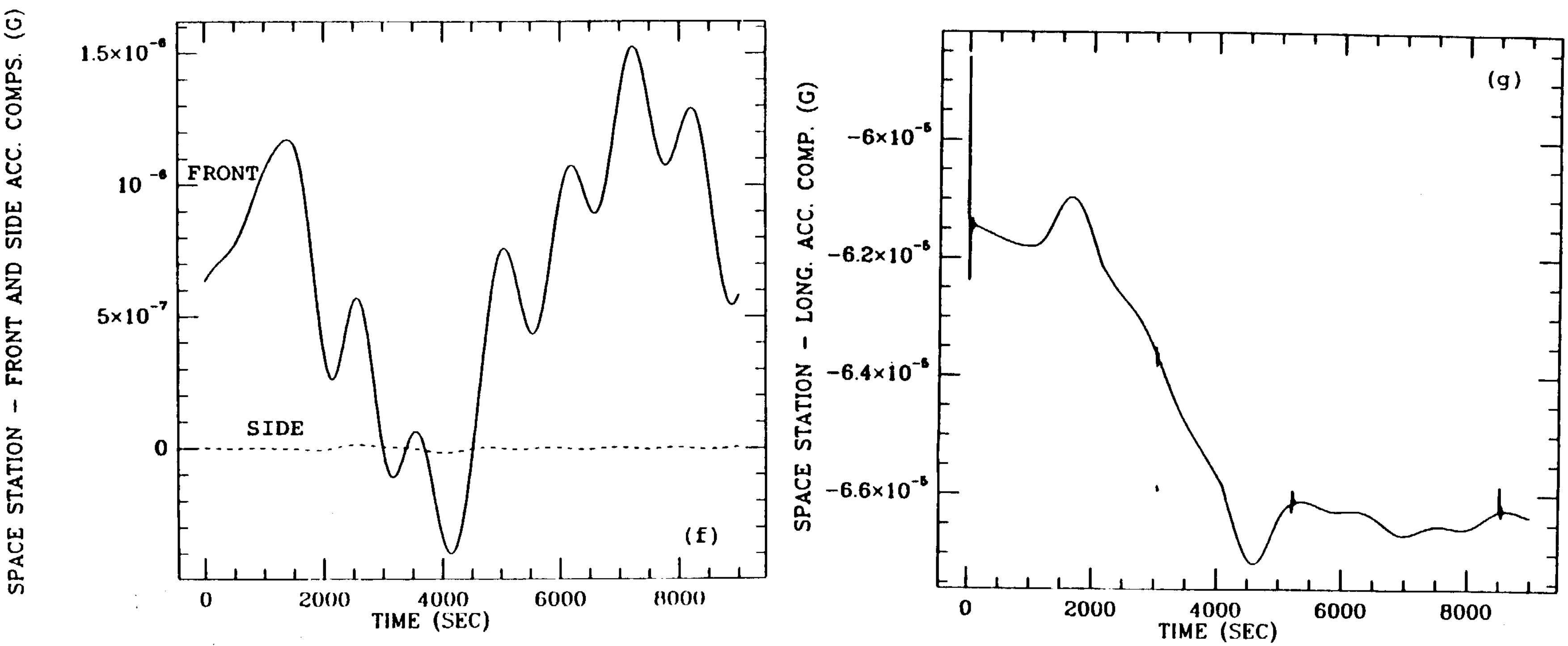
  —1404 m $\rightarrow$ 2667 m FROM 5×10^{-4} G TO 10^{-3} G

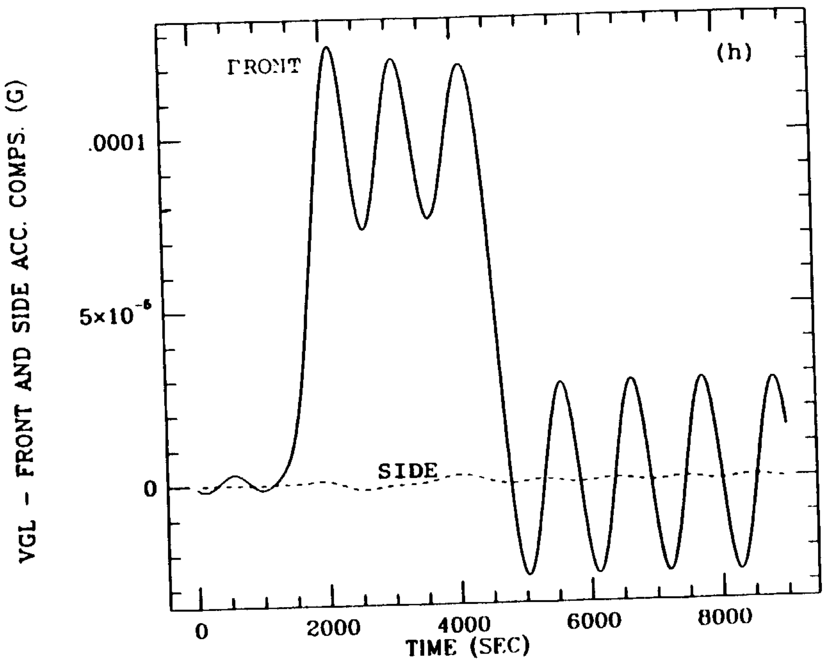
  —ONLY LONGITUDINAL DAMPERS ACTIVATED

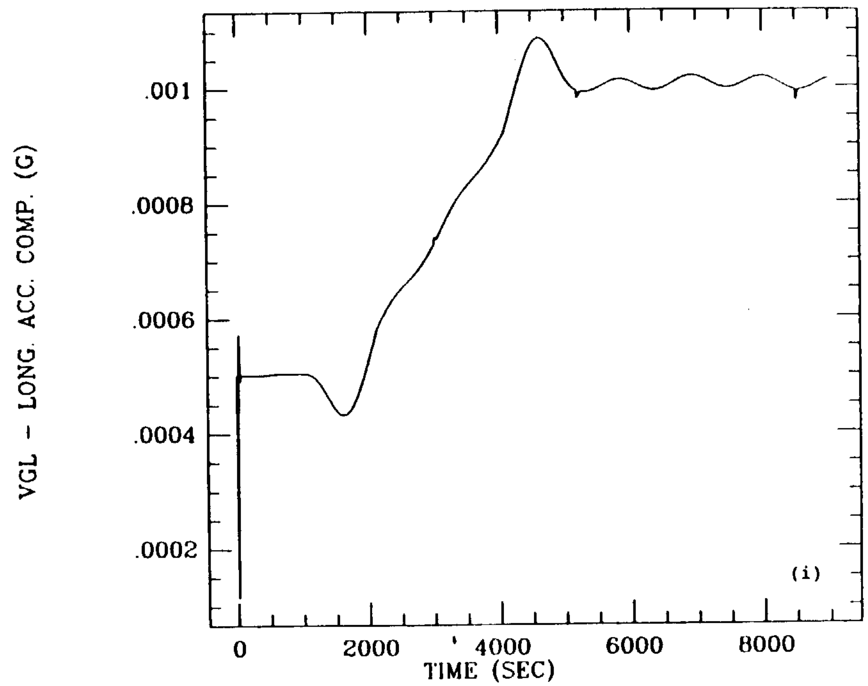
  —$1/\alpha$ = 1000 S






SPACE STATION - FRONT AND SIDE ACC. COMPS. (G)
1.5×10⁻⁶
10⁻⁶
5×10⁻⁷
0
FRONT
SIDE
(f)
0
2000
4000
6000
8000
TIME (SEC)
SPACE STATION - LONG. ACC. COMP. (G)
-6×10⁻⁵
-6.2×10⁻⁵
-6.4×10⁻⁵
-6.6×10⁻⁵
(g)
0
2000
4000
6000
8000
TIME (SEC)





- FRONT ACCELERATION COMPONENT STRONGLY INFLUENCED BY UNDAMPED LATERAL OSCILLATIONS.

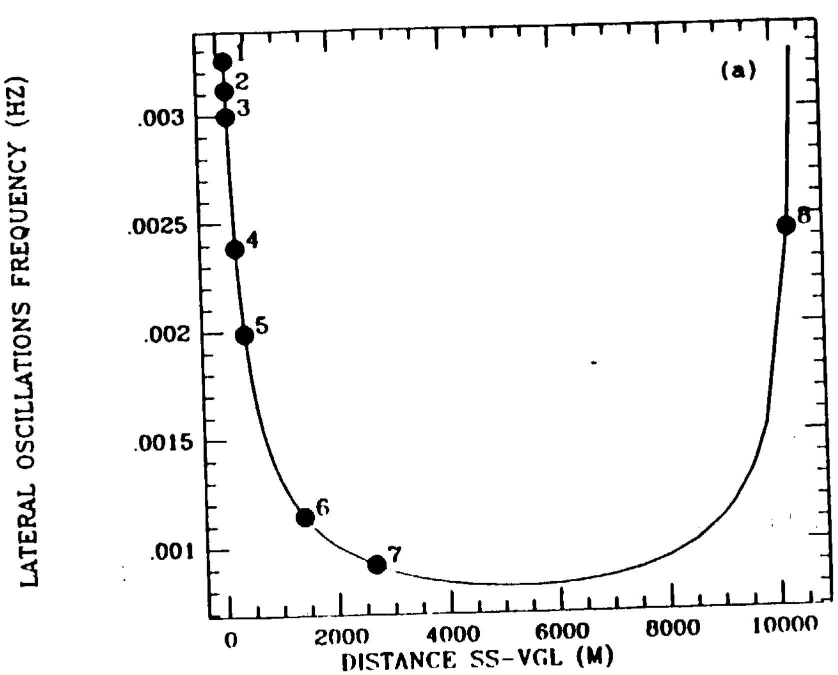
- DETUNING OF LONGITUDINAL DAMPERS DOES NOT AFFECT APPRECIABLY LONGITUDINAL ACCELERATION COMPONENT.

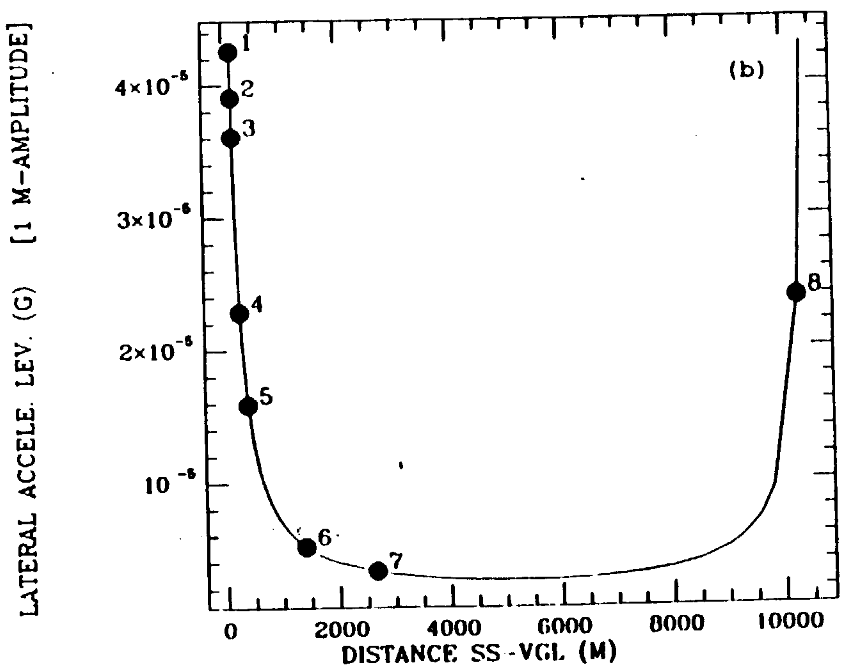
OSCILLATION DAMPERS

	DAMPING ACTION
1. LONGITUDINAL OSCILLATIONS	
—PLATFORM OSCILLATIONS	LONGITUDINAL DAMPERS (PASSIVE)
—TETHER VIBRATIONS	TETHER MATERIAL (PASSIVE)
2. TRANSVERSE OSCILLATIONS	
—PLATFORM OSCILLATIONS	TRANSVERSE DAMPER (ACTIVE CONTROL OF TETHER LENGTH)
—TETHER VIBRATIONS	TETHER MATERIAL (THROUGH NON-LINEAR COUPLING)
3. LIBRATIONS	
ENTIRE SYSTEM	LIBRATION DAMPER (ACTIVE CONTROL OF TETHER LENGTH)
4. ATTITUDE OSCILLATIONS	
—PLATFORMS	ATTITUDE DAMPERS (ACTIVE OR PASSIVE)

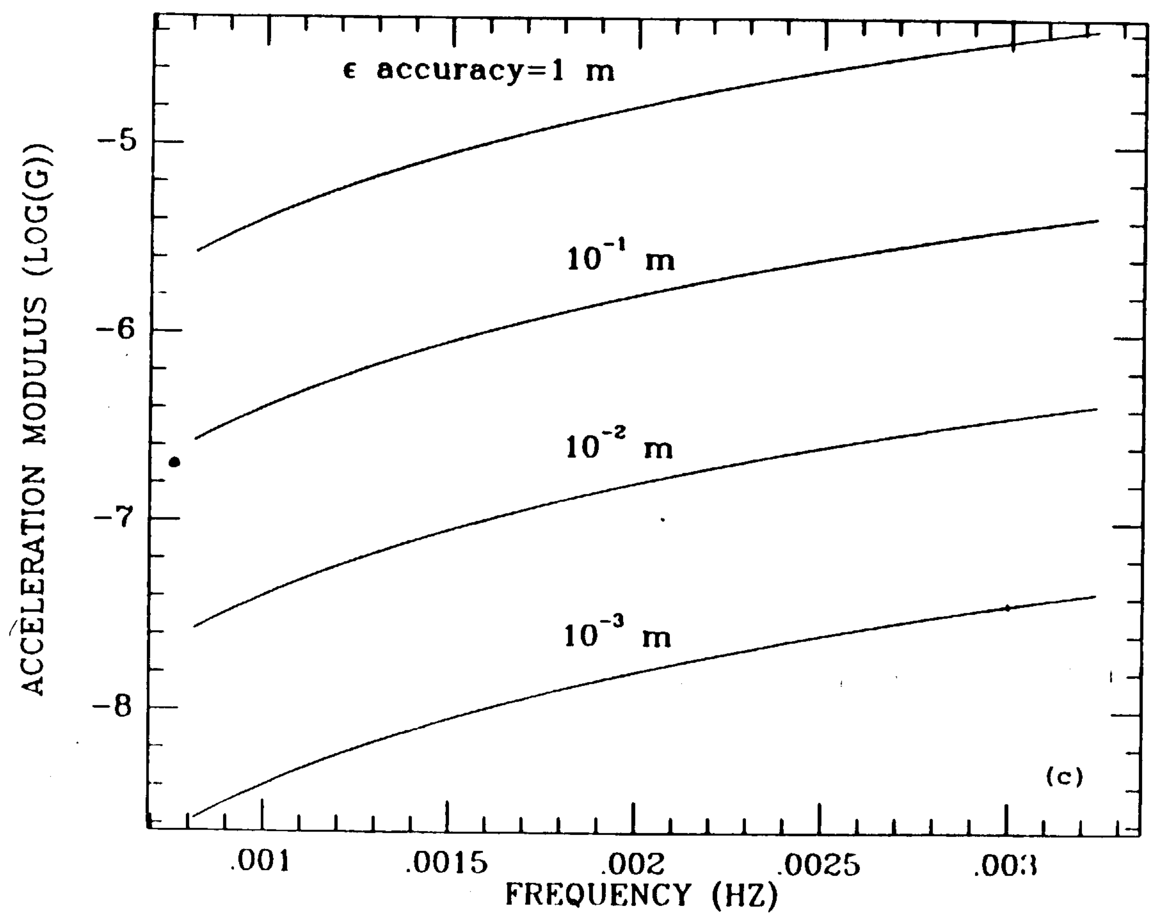
LATERAL OSCILLATIONS OF VGL

- 1 DOF MODEL: ELEVATOR SUSPENDED ELASTICALLY IN BETWEEN SS AND END-MASS





- POSITION DETERMINATION ACCURACY REQUIRED FOR SPECIFIED ACCELERATION LEVEL



LATERAL/LIBRATIONAL DAMPER

- LATERAL OSCILLATION AND LIBRATION DAMPED BY CONTROLLING ACTIVELY THE TETHER SEGMENTS' LENGTHS
- PHYSICS: GENERATE CORIOLIS FORCES OPPOSED TO THE OSCILLATION TO BE DAMPED OUT
- MATHEMATICS:

—IN-PLANE LIBRATION CONTROL $\Delta\ell_i = -\ell_{oi} k_\theta \theta$ $\quad$ i=1,2 $\quad$ θ=in-plane libration

—IN-PLANE TRANSVERSE OSCILLATION CONTROL

$$\Delta\ell_1 = k_\epsilon \epsilon; \qquad \Delta\ell_2 = -\frac{\ell_{o1}}{\ell_{o2}} k_\epsilon \epsilon$$

ϵ = IN-PLANE LATERAL DEFLECTION

- OUT-OF-PLANE LIBRATION AND LATERAL OSCILLATION ARE NEGLIGIBLE

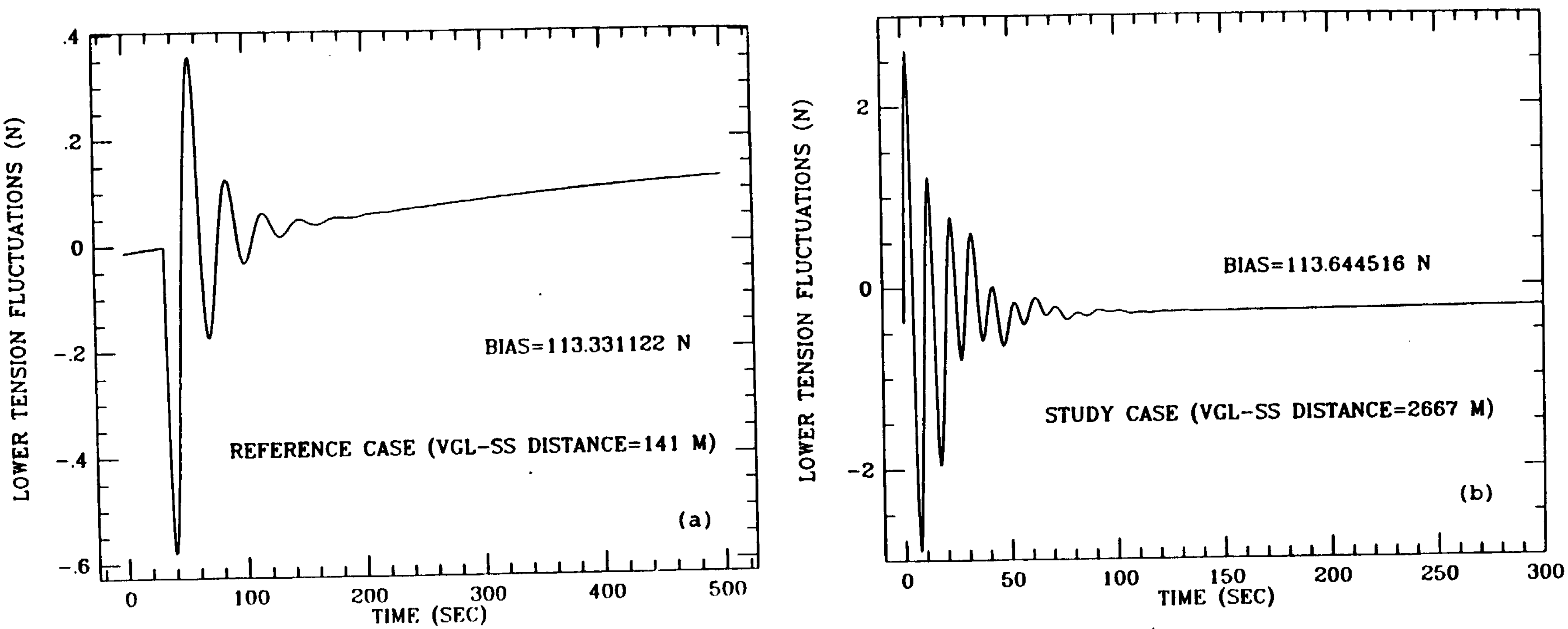
DETUNING OF LONGITUDINAL DAMPERS

- SINCE LONGITUDINAL DAMPERS ARE PASSIVE AND TUNED TO A SPECIFIC FREQUENCY THEIR PERFORMANCE DECAYS AS THE ELEVATOR MOVES AWAY FROM THE TUNING POSITION

Table 2 System's Longitudinal Frequencies vs. VGL-SS Distance

$\ell_2(m)$	I modal frequency (Hz)	II modal frequency (Hz)
141	4.88×10^{-1}	2.80×10^{-2}
154	4.67×10^{-1}	2.80×10^{-2}
167	4.48×10^{-1}	2.80×10^{-2}
268	3.54×10^{-1}	2.81×10^{-2}
394	2.92×10^{-1}	2.83×10^{-2}
1404	1.56×10^{-1}	2.94×10^{-2}
2667	1.15×10^{-1}	3.12×10^{-2}
10242	2.36×10^{-1}	4.31×10^{-2}

- RESPONSE TO IMPULSE FOR TWO POSITIONS OF ELEVATOR



- MODERATE DECAY OF PERFORMANCE DUE TO DETUNING. DAMPING RATIO FROM 18% TO 13% AS ELEVATOR MOVES FROM THE 141 M POSITION TO THE 2667 M POSITION.

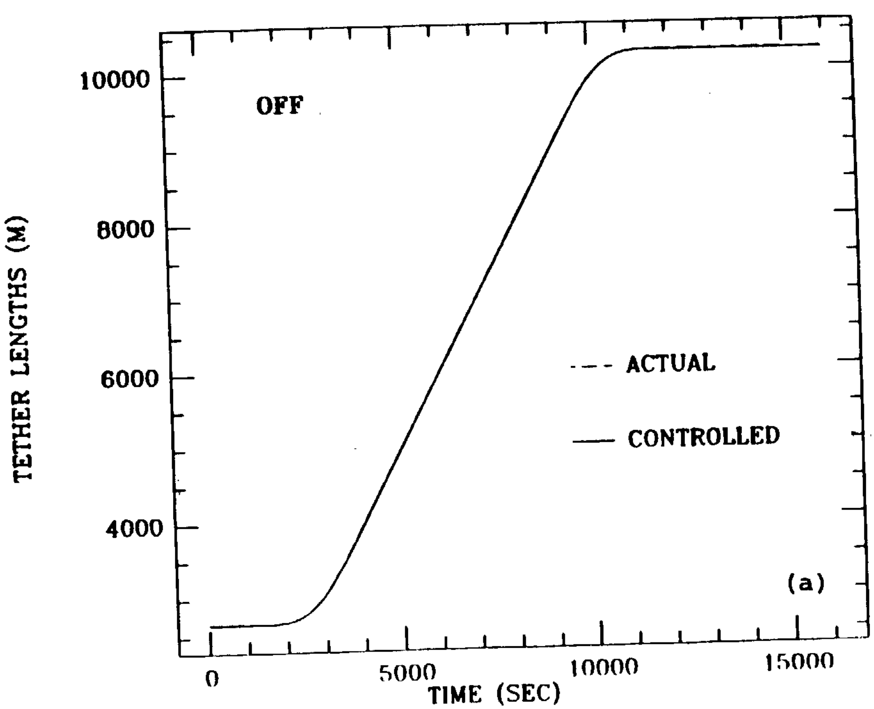
MORE TRANSIENT DYNAMICS

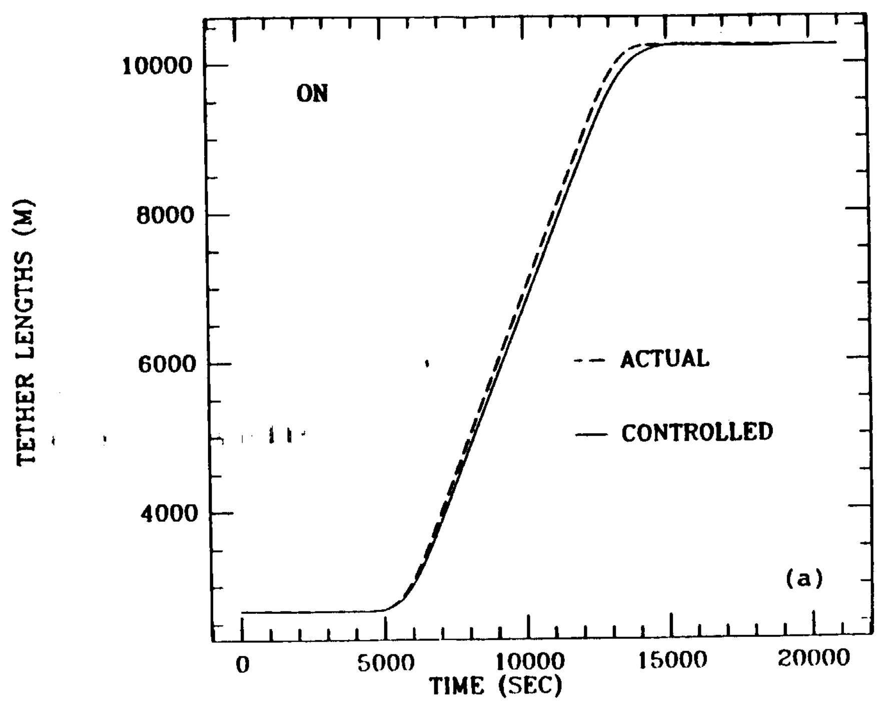
- DYNAMIC RESPONSE OF LONG DISTANCE CRAWLING MANEUVERS

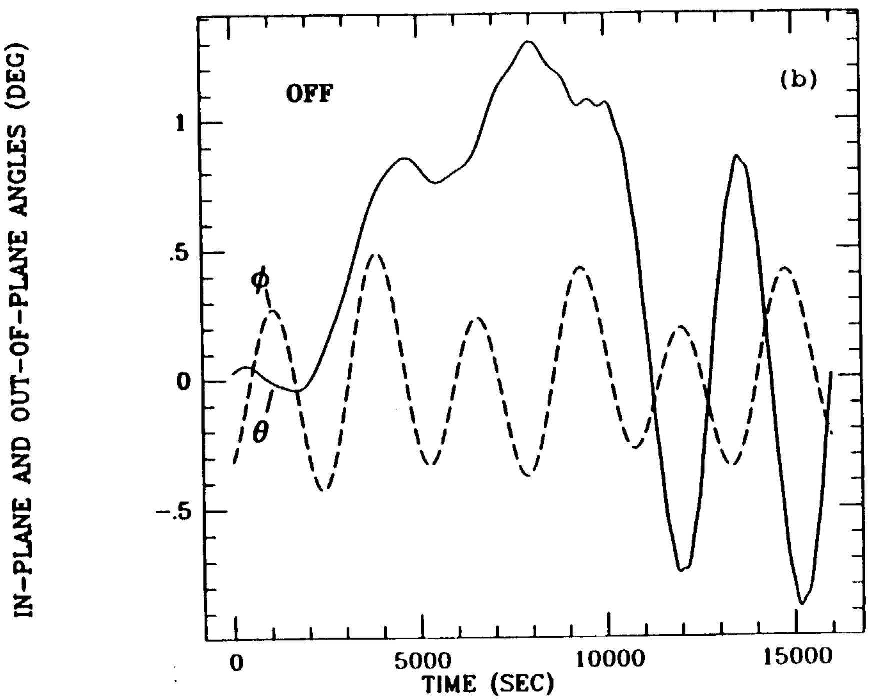
  —2667 M $\rightarrow$ 10242 M OR FROM 10^{-3} G TO 4×10^{-3} G

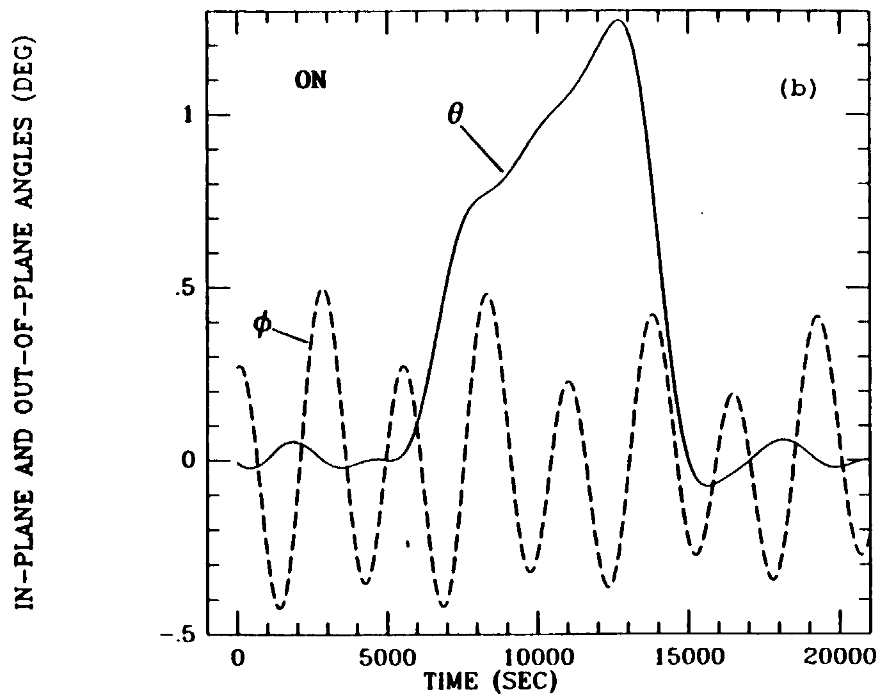
  —$1/\alpha$ = 2600 S

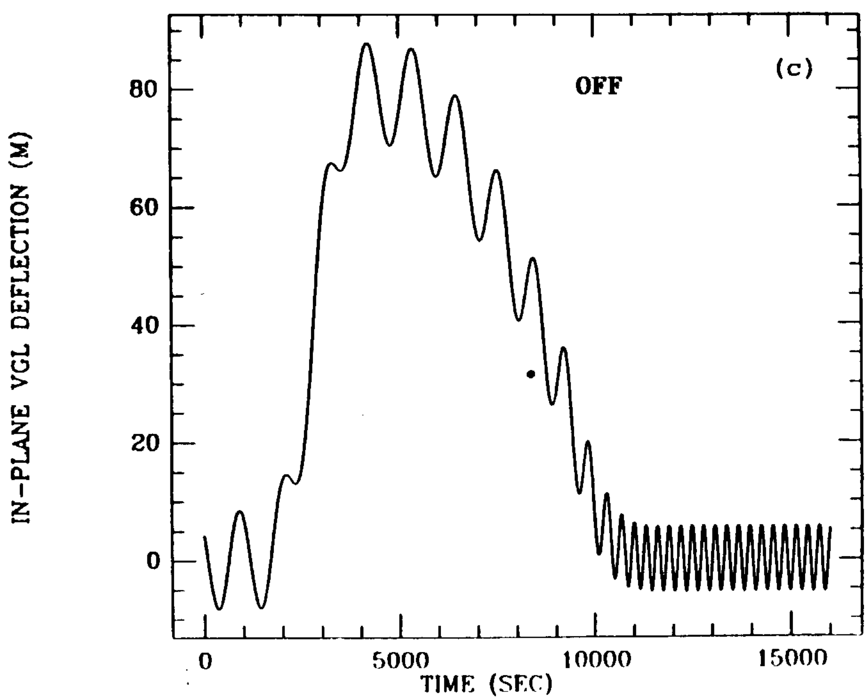
  —LIBRATION/LATERAL DAMPERS ON (K_θ=K_ϵ=1) VERSUS DAMPERS OFF



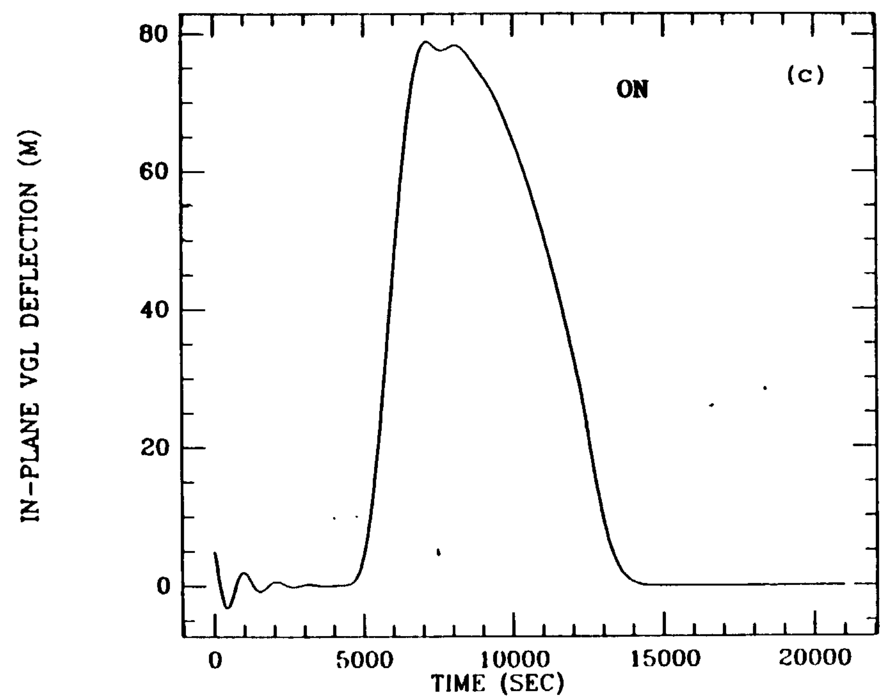



IN-PLANE AND OUT-OF-PLANE ANGLES (DEG)
OFF
(b)
ϕ
θ
1
.5
0
-.5
0
5000
10000
15000
TIME (SEC)

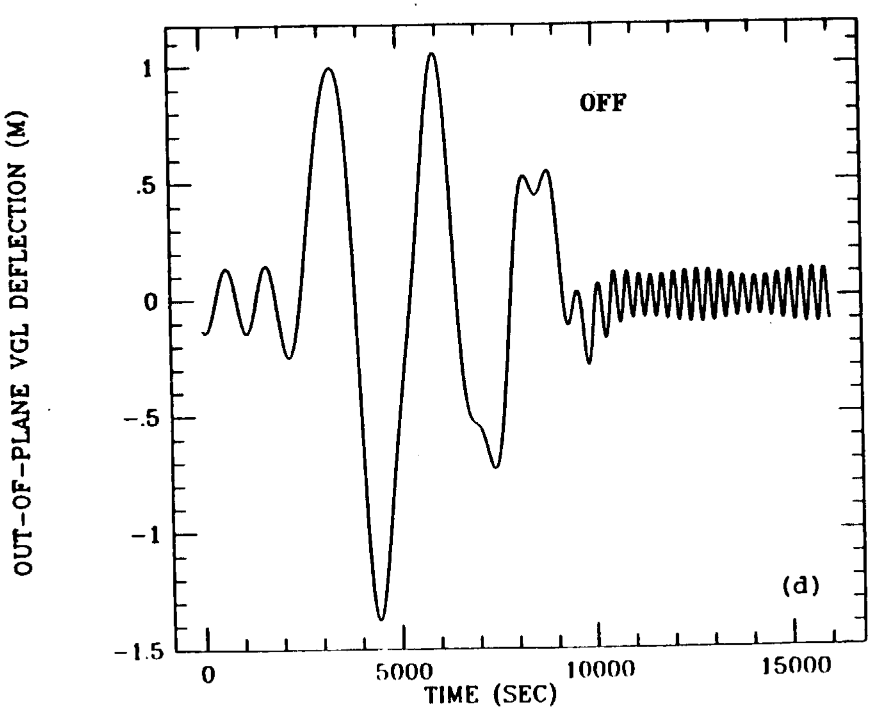

IN-PLANE AND OUT-OF-PLANE ANGLES (DEG)
ON
(b)
θ
ϕ
1
.5
0
-.5
0
5000
10000
15000
20000
TIME (SEC)



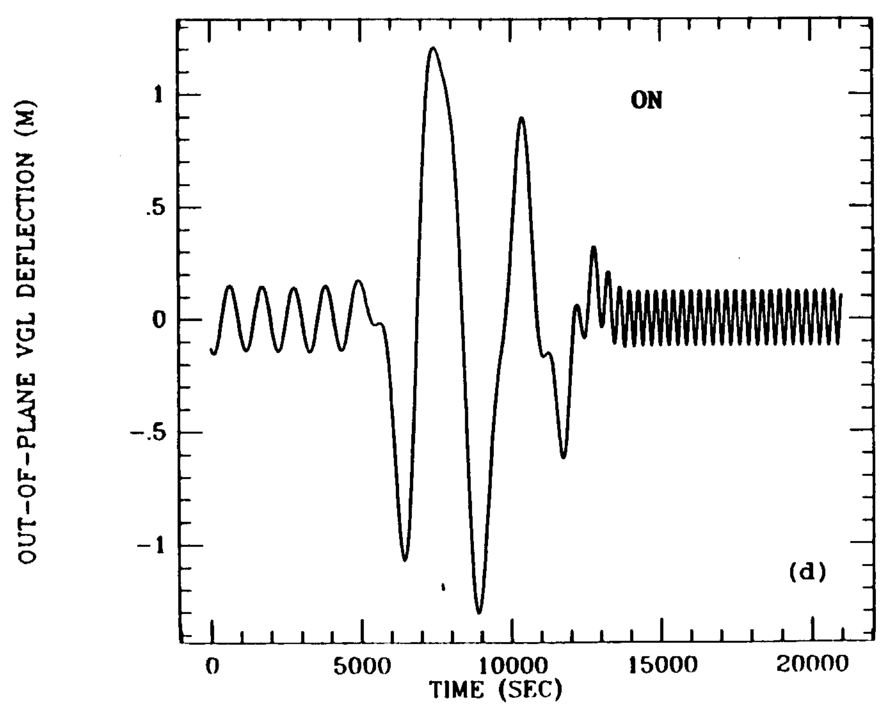
IN-PLANE VGL DEFLECTION (M)
TIME (SEC)
OFF
(c)



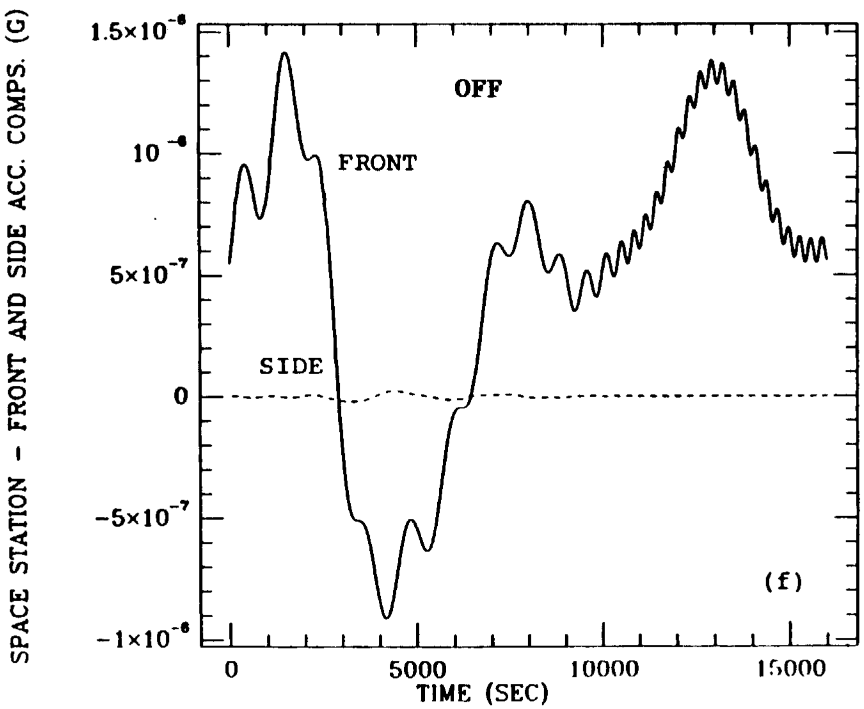
IN-PLANE VGL DEFLECTION (M)
TIME (SEC)
ON
(c)

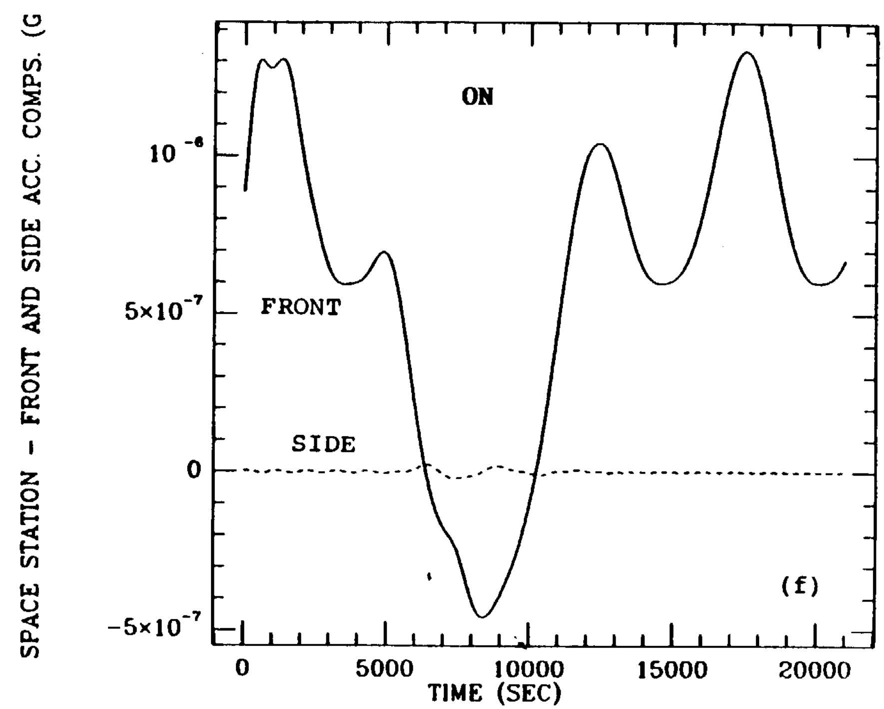


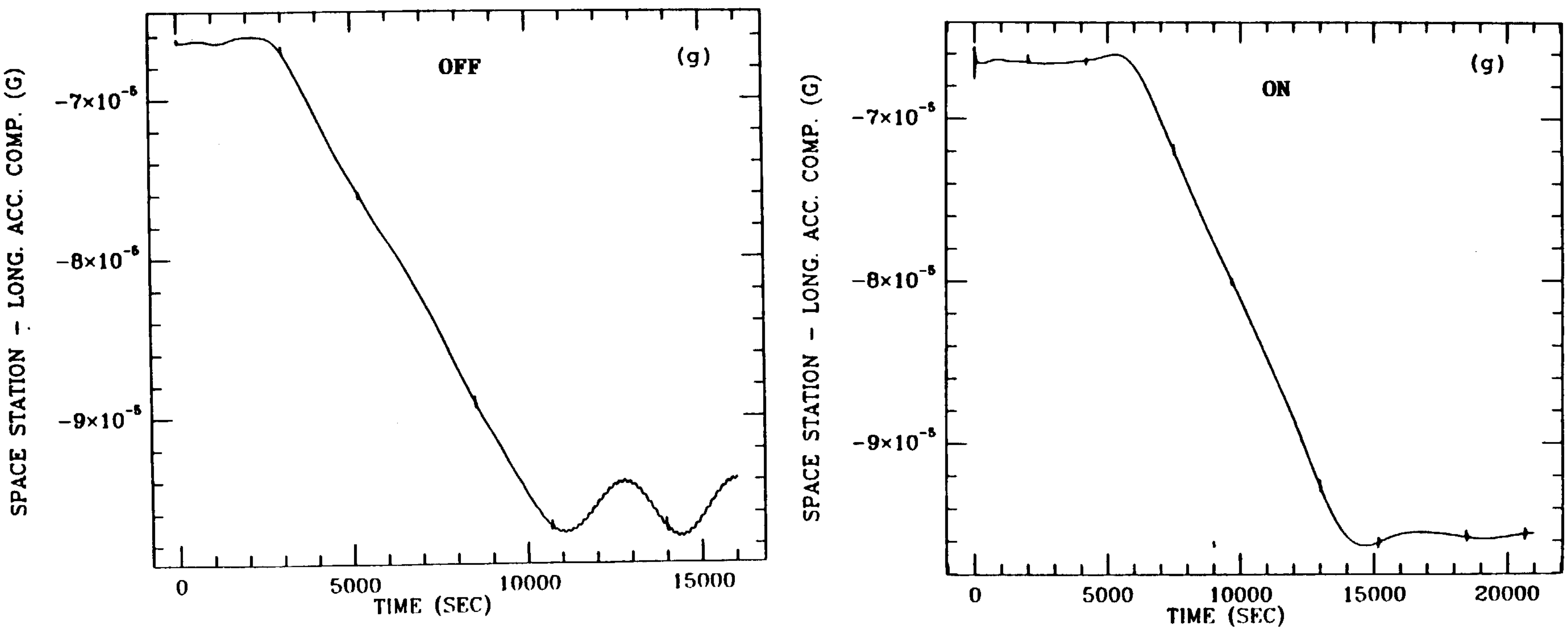
OUT-OF-PLANE VGL DEFLECTION (M)
1
.5
0
-.5
-1
-1.5
OFF
(d)
0
5000
10000
15000
TIME (SEC)



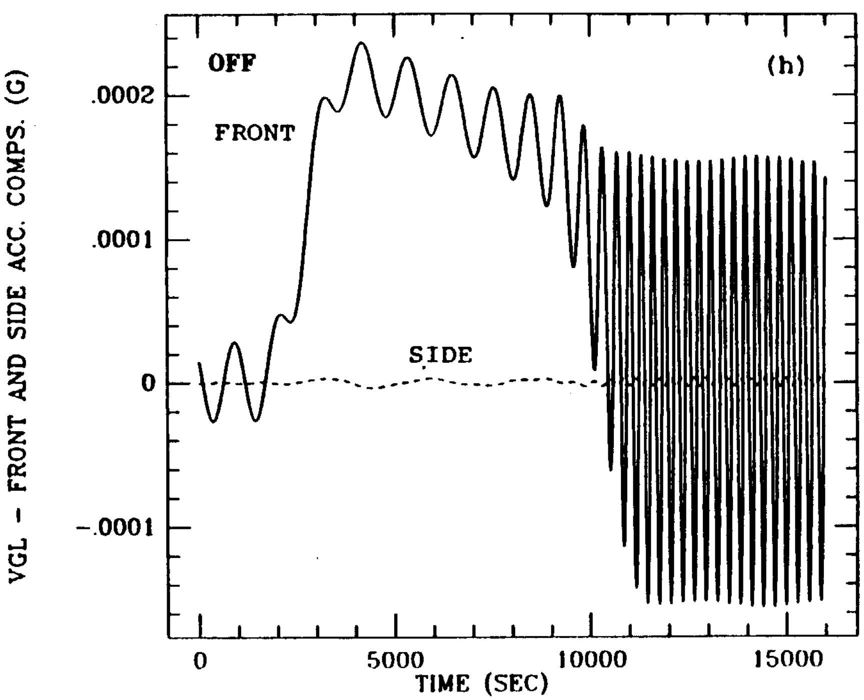
OUT-OF-PLANE VGL DEFLECTION (M)
1
.5
0
-.5
-1
ON
(d)
0
5000
10000
15000
20000
TIME (SEC)

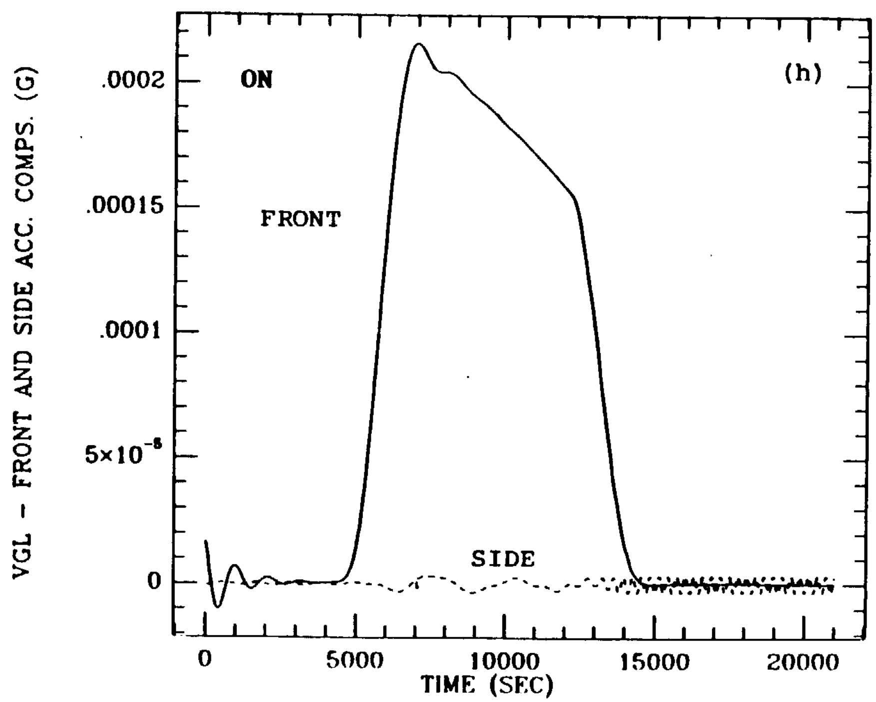

SPACE STATION - FRONT AND SIDE ACC. COMPS. (G)
1.5×10⁻⁶
10⁻⁶
5×10⁻⁷
0
−5×10⁻⁷
−1×10⁻⁶
OFF
FRONT
SIDE
(f)
0
5000
10000
15000
TIME (SEC)

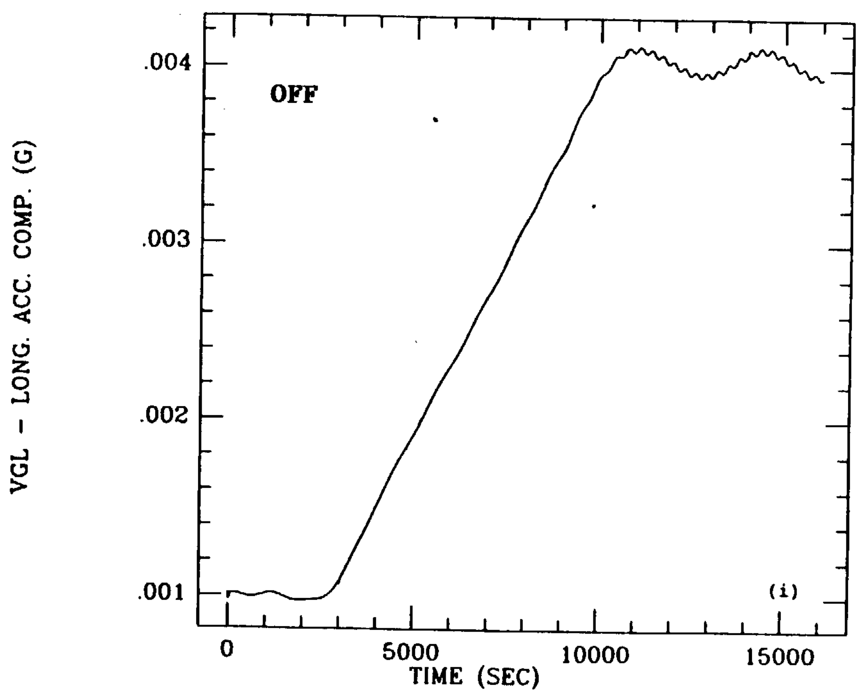

SPACE STATION - FRONT AND SIDE ACC. COMPS. (G
10⁻⁶
5×10⁻⁷
0
−5×10⁻⁷
ON
FRONT
SIDE
(f)
0
5000
10000
15000
20000
TIME (SEC)

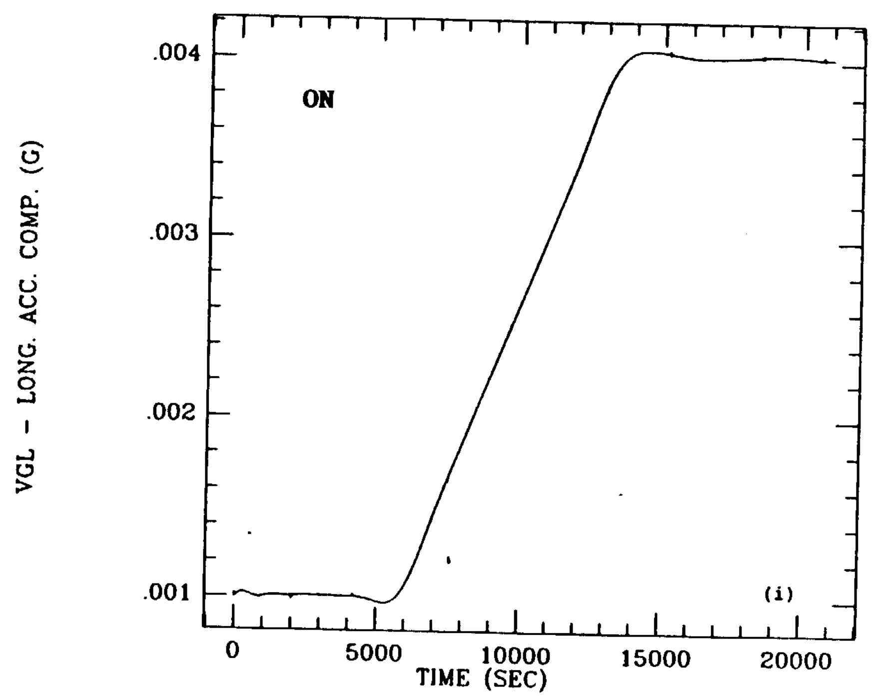


SPACE STATION – LONG. ACC. COMP. (G)
-7×10^{-5}
-8×10^{-5}
-9×10^{-5}
OFF
(g)
0
5000
10000
15000
TIME (SEC)
SPACE STATION – LONG. ACC. COMP. (G)
-7×10^{-5}
-8×10^{-5}
-9×10^{-5}
ON
(g)
0
5000
10000
15000
20000
TIME (SEC)


OFF
(h)
FRONT
SIDE
VGL - FRONT AND SIDE ACC. COMPS. (G)
.0002
.0001
0
-.0001
0
5000
10000
15000
TIME (SEC)


ON
(h)
FRONT
SIDE
VGL - FRONT AND SIDE ACC. COMPS. (G)
.0002
.00015
.0001
5×10⁻⁵
0
0
5000
10000
15000
20000
TIME (SEC)


VGL - LONG. ACC. COMP. (G)
.004
.003
.002
.001
OFF
(i)
0
5000
10000
15000
TIME (SEC)


VGL - LONG. ACC. COMP. (G)
.004
.003
.002
.001
ON
(i)
0
5000
10000
15000
20000
TIME (SEC)

CONCLUSIONS ON CRAWLING MANEUVERS

- MIRROR-IMAGE MOTION CONTROL LAW IS SUITABLE FOR SHORT, MEDIUM AND LONG DISTANCE MANEUVERS BY SIMPLY ADJUSTING THE TIME CONSTANT.

- LONGITUDINAL DAMPERS REQUIRED FOR ALL MANEUVERS

- LIBRATIONAL/LATERAL DAMPERS REQUIRED ONLY FOR MEDIUM/LONG DISTANCE MANEUVERS

- DETUNING OF PASSIVE LONGITUDINAL DAMPERS DOES NOT IMPAIR THEIR PERFORMANCE SIGNIFICANTLY

FAST CRAWLING MANEUVERS (FCM)

- SOME EXPERIMENTS DO NOT SET LIMITS ON ACCELERATION LEVELS DURING TRANSFER MANEUVERS

- FASTER CRAWLING IS CONVENIENT AND POSSIBLE FOR MODERATE DISTANCE TRANSFER MANEUVERS
  - –MODEST ADVANTAGES FOR SHORT DISTANCE MANEUVERS
  - –LONG DISTANCE MANEUVERS ALREADY LIMITED BY MAXIMUM CRAWLING SPEED

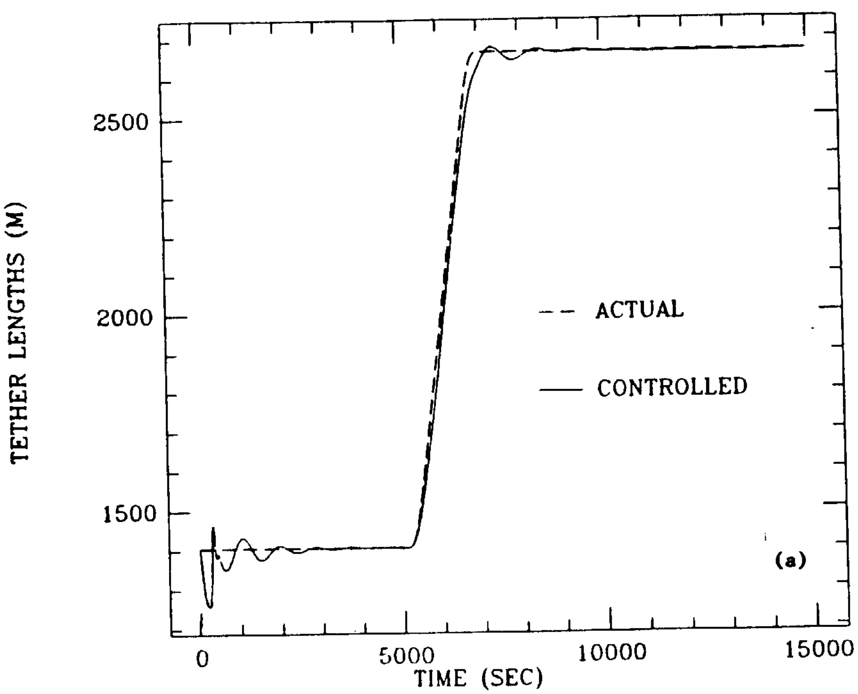
- MANEUVERS TOO FAST EXCITE LONG TRANSIENT OSCILLATIONS OF THE SYSTEM

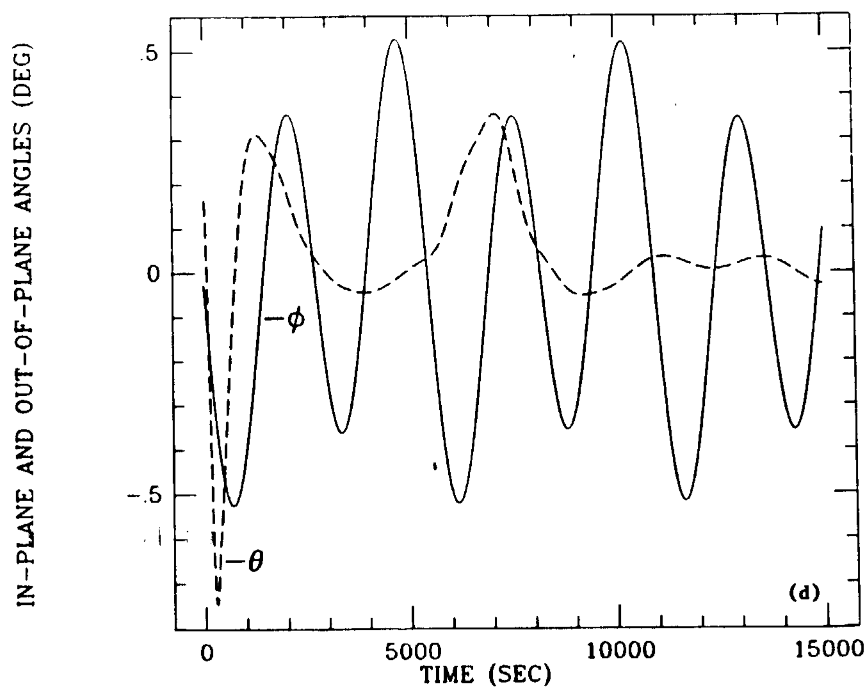
- TRANSIENT DYNAMICS OF A FCM (AN EXAMPLE)

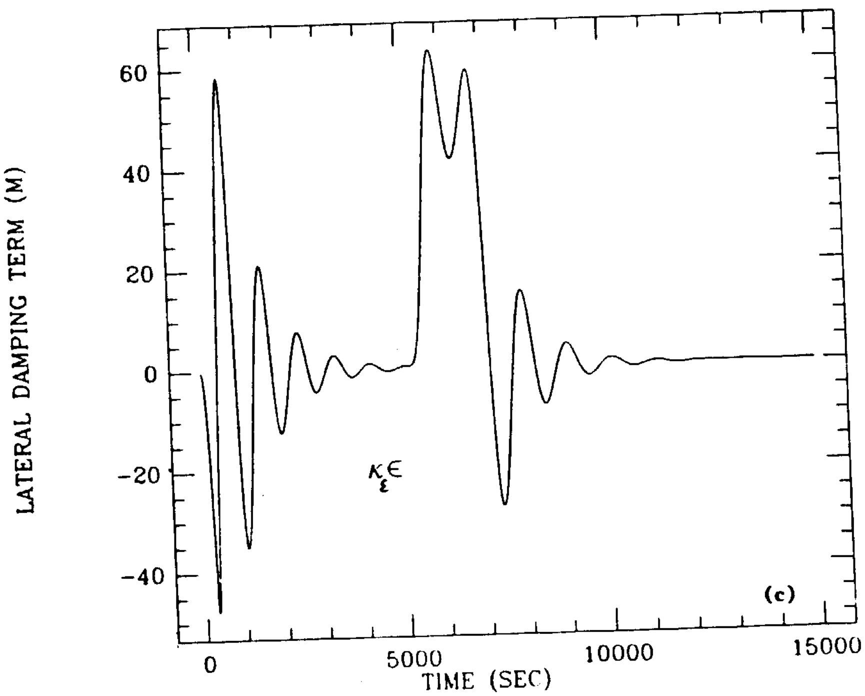
  —1404 M $\rightarrow$ 2667 M OR FROM 5 $\times$ 10^{-4} G TO 10^{-3} G

  —ALL DAMPERS ACTIVATED (K_θ=K_ϵ=1)

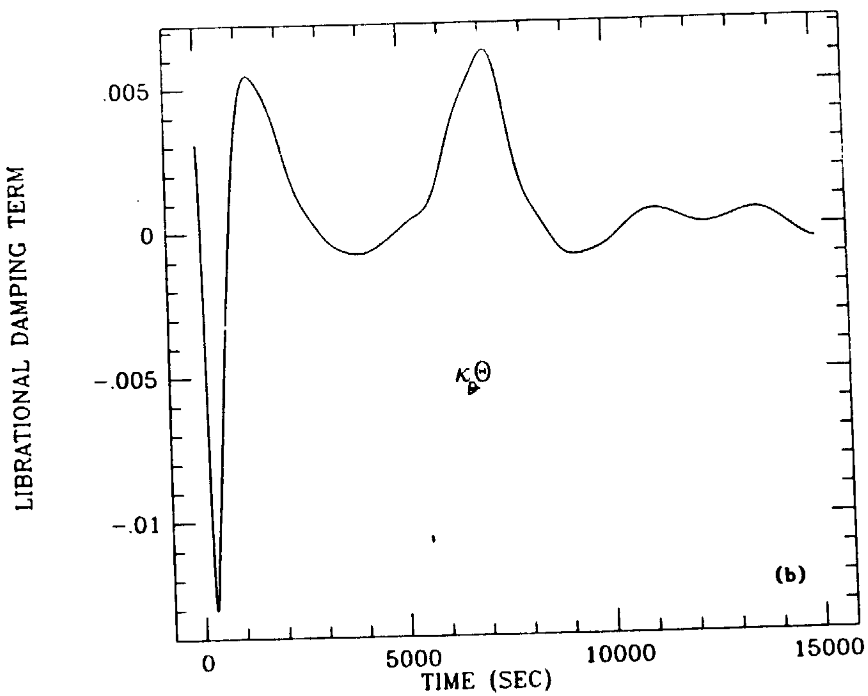
  —TIME CONSTANT REDUCED FROM 1000 S TO 500 S





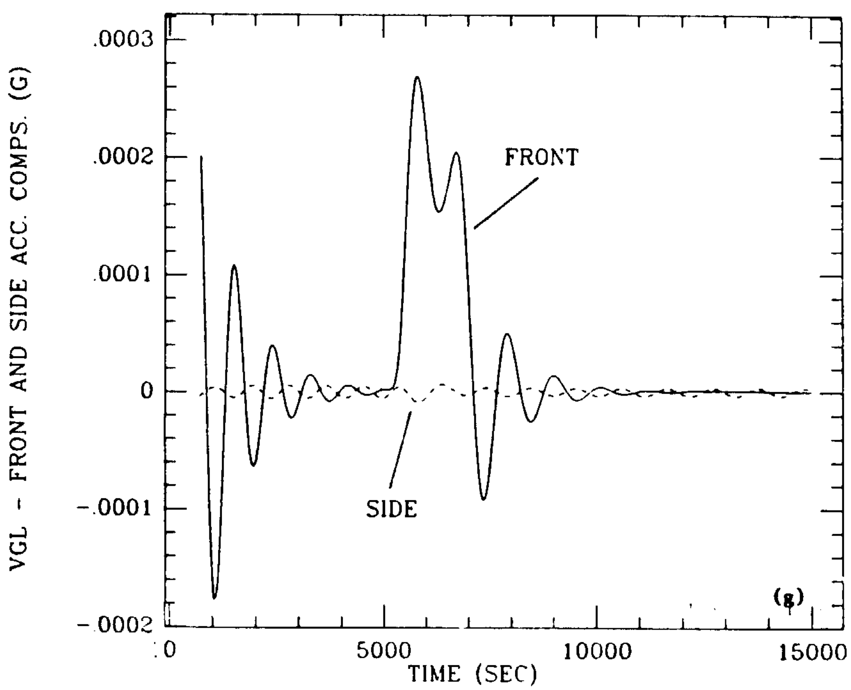


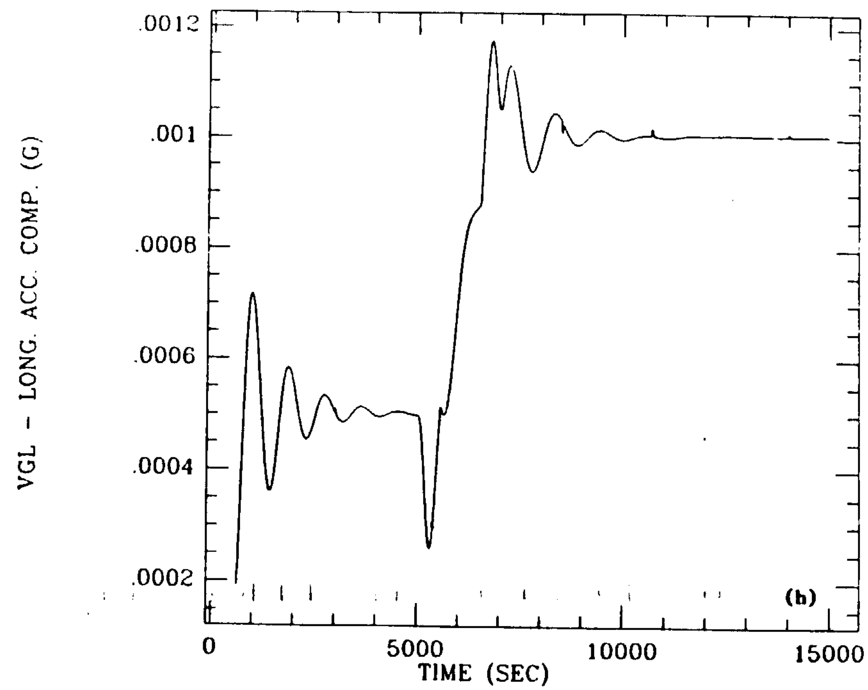
LATERAL DAMPING TERM (M)
60
40
20
0
-20
-40
0
5000
10000
15000
TIME (SEC)
$\kappa_\xi \epsilon$
(c)



LIBRATIONAL DAMPING TERM
.005
0
-.005
-.01
0
5000
10000
15000
TIME (SEC)
$\kappa_\theta \Theta$
(b)

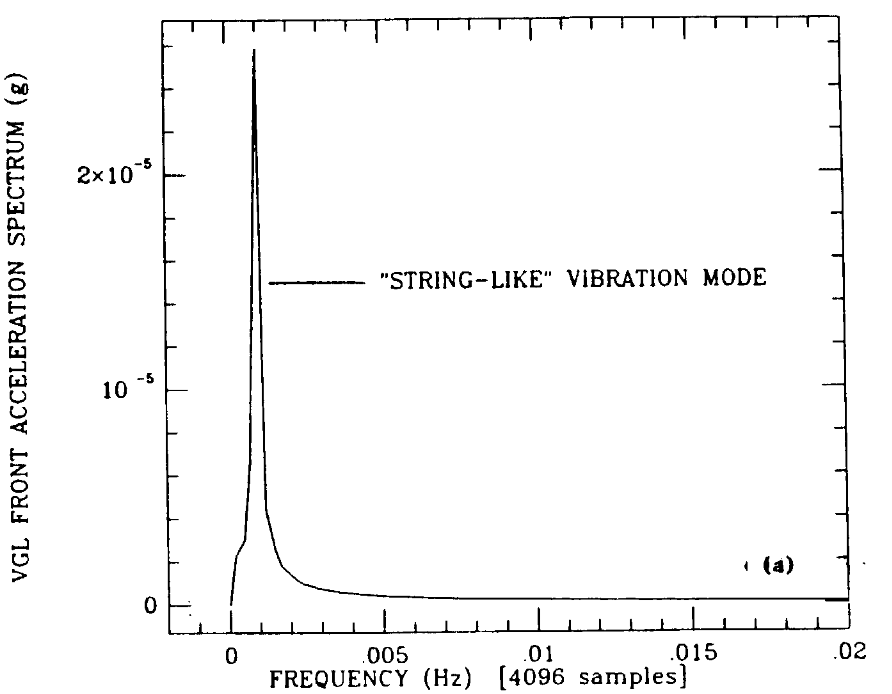
- FAST CRAWLING MANEUVERS POSSIBLE OVER MODERATE DISTANCES IF ACCELERATION LEVELS DURING TRANSFER ARE NOT A CONCERN.

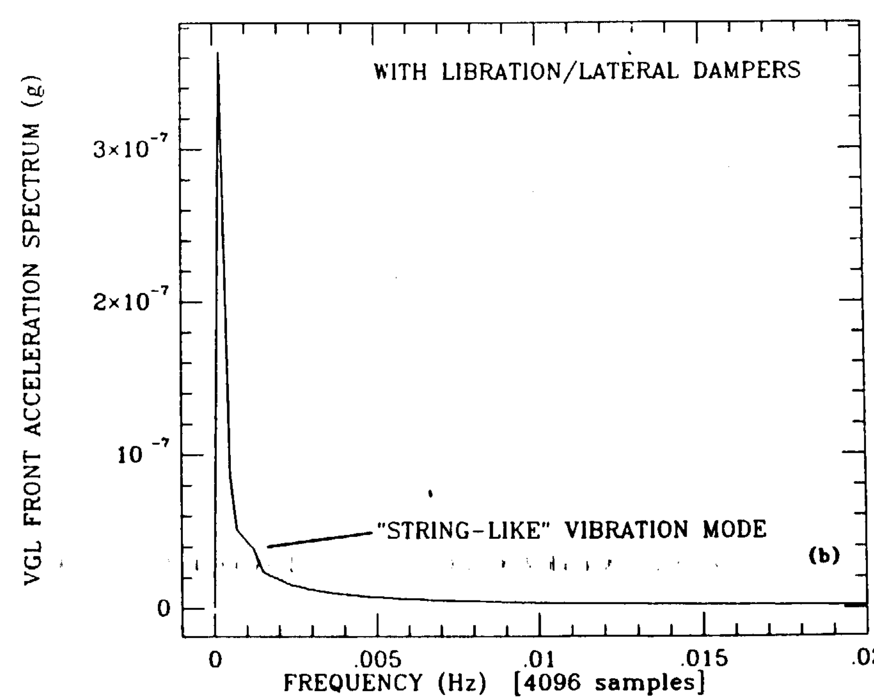




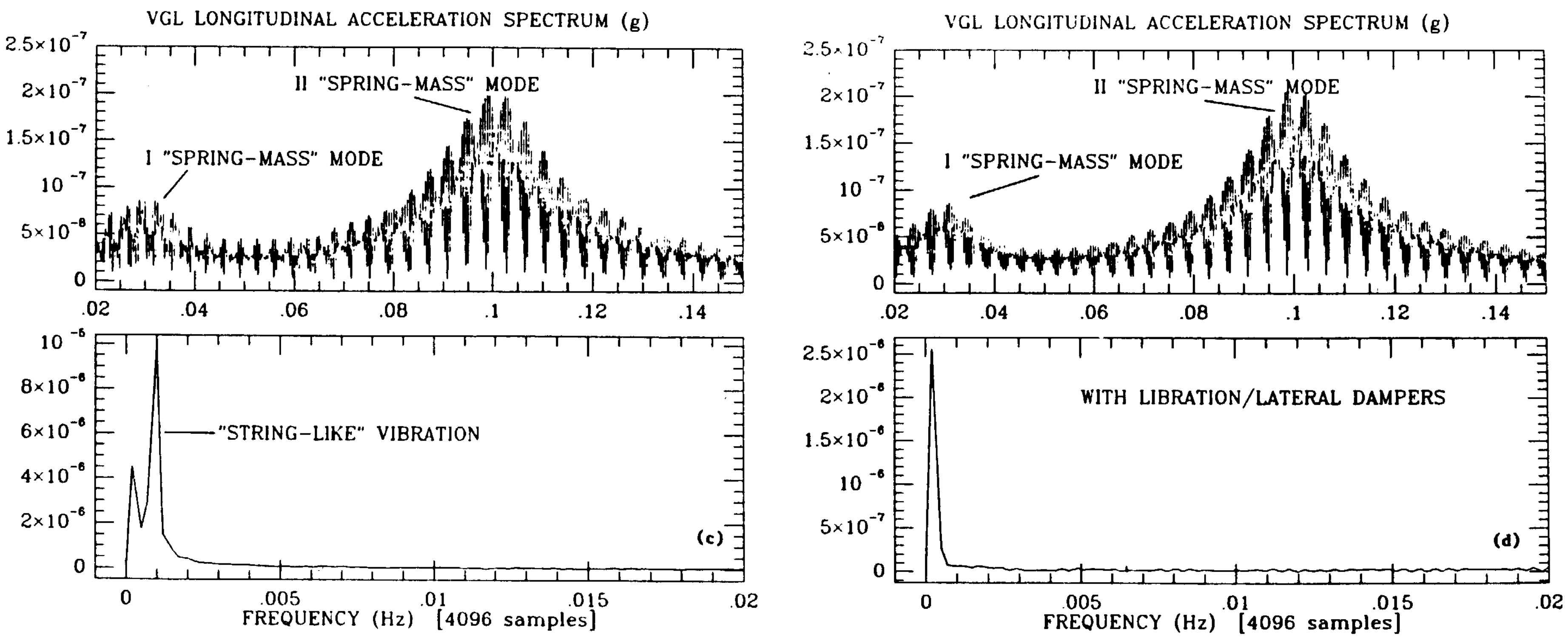
FREQUENCY ANALYSIS OF ACCELERATIONS ON BOARD VGL

- EXAMPLE: ELEVATOR AT 2667 M FROM SS AFTER A TRANSFER MANEUVER
- LIBRATIONAL/LATERAL DAMPERS ON VERSUS DAMPERS OFF





- AMPLITUDES STRONGLY REDUCED BY ACTIVATION OF LIB./LAT. DAMPERS


VGL LONGITUDINAL ACCELERATION SPECTRUM (g)
II "SPRING-MASS" MODE
I "SPRING-MASS" MODE
"STRING-LIKE" VIBRATION
(c)
FREQUENCY (Hz) [4096 samples]
VGL LONGITUDINAL ACCELERATION SPECTRUM (g)
II "SPRING-MASS" MODE
I "SPRING-MASS" MODE
WITH LIBRATION/LATERAL DAMPERS
(d)
FREQUENCY (Hz) [4096 samples]

ACCELERATION NOISE ON BOARD VGL

1. ENVIRONMENTAL PERTURBATIONS

   —J_2, ATMOSPHERIC DRAG, THERMAL DISTURBANCES, ETC.

2. TETHER-RELATED ACCELERATIONS

   —LONGITUDINAL AND LATERAL OSCILLATIONS

3. VGL-RELATED ACCELERATIONS

   —STRUCTURAL, ATTITUDE MOTION, OUTGASSING, MAN-MADE, ETC.

4. SS-RELATED ACCELERATIONS

   —STRUCTURAL, ATTITUDE MOTION, MACHINERIES, MAN-MADE, ETC.

SS-RELATED DISTURBANCES/PROPAGATION ALONG TETHER

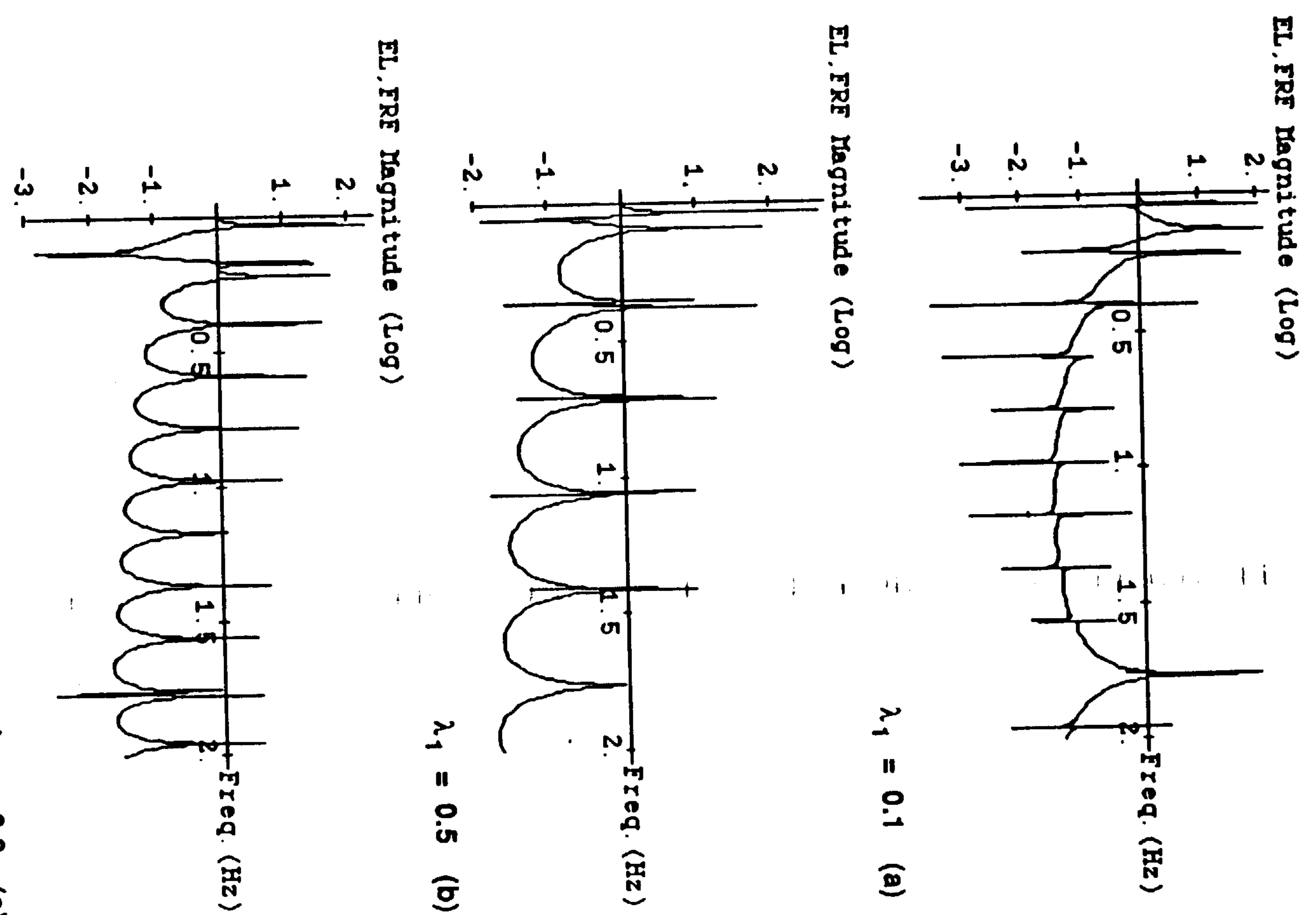
- DISTURBANCES
  - —$f \simeq 10^{-3}$ Hz: AERODYNAMIC AND ORBITAL PERTURBATIONS
  - —10^{-2} Hz $< f <$ 10 Hz: STRUCTURAL VIBRATIONS
  - —$f >$ 10 Hz: MACHINERIES, HUMAN ACTIVITIES

- MODEL
  - —WAVE EQUATIONS OF THE TWO-TETHER-SEGMENT SYSTEM WITH MASSIVE PLATFORMS
  - —SMALL OSCILLATIONS
  - —VISCOUS MATERIAL DAMPING
  - —UNCONSTRAINED PLATFORMS

- FREQUENCY RESPONSE FUNCTION (FRF) AT VGL FOR A PERTURBATION ORIGINATED AT SS

  – NO MATERIAL DAMPING

  – λ_1 = NON-DIMENSIONAL DISTANCE BETWEEN VGL AND SS

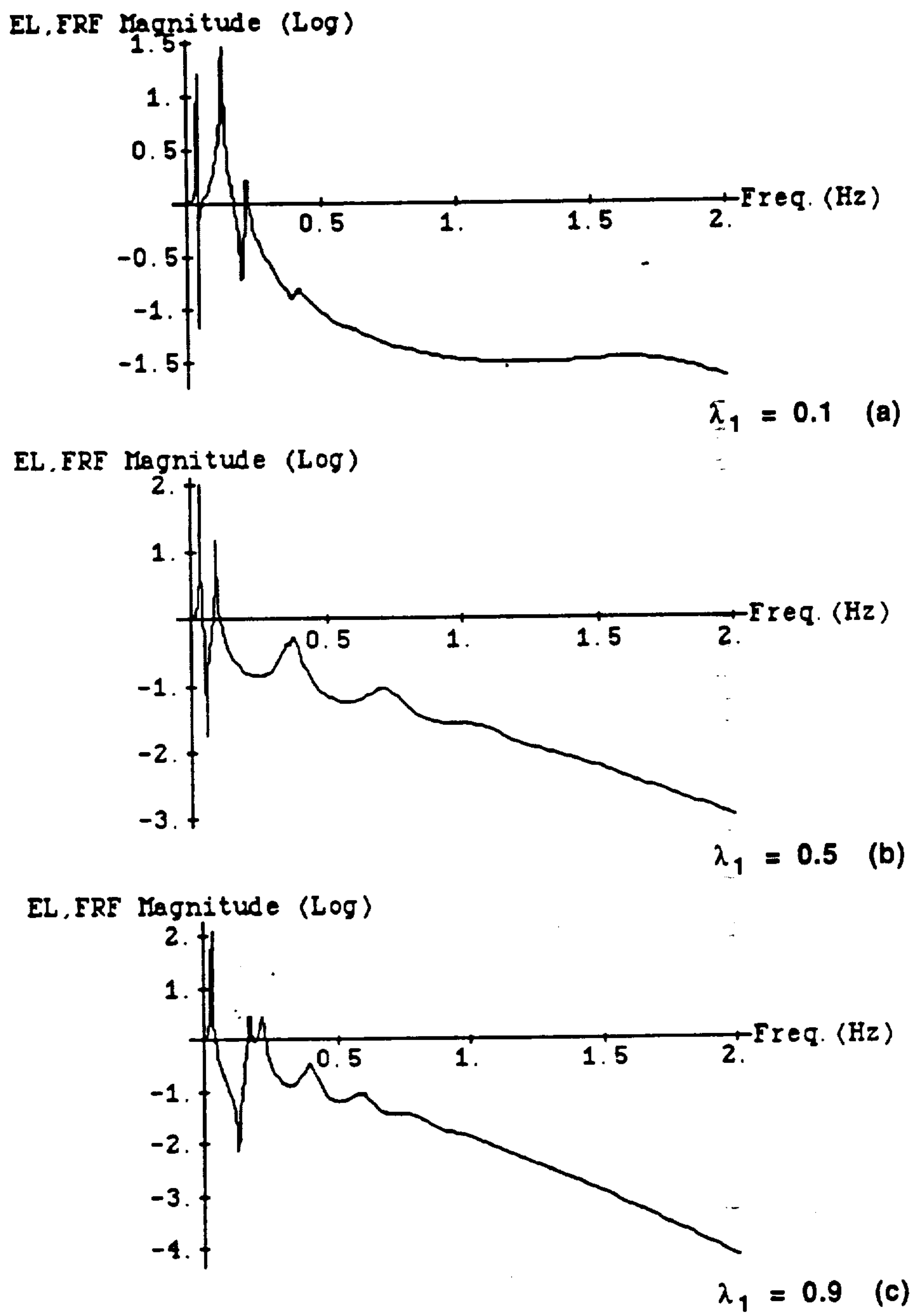


λ_1 = 0.1 (a)

λ_1 = 0.5 (b)

λ_1 = 0.9 (c)

—DAMPING RATIO OF FIRST LONGITUDINAL MODE = 2%



CONCLUSIONS ON DISTURBANCE PROPAGATION

- LOW FREQUENCY DISTURBANCES (< 0.2 Hz) PROPAGATE WITH ALMOST NO ATTENUATION
  - —SELECTED TETHERS ARE TOO STIFF FOR FILTERING OUT LOW FREQUENCY DISTURBANCES
- ATTENUATORS ARE REQUIRED AT SS TETHER ATTACHMENT POINT
- SOFTER TETHERS WOULD BE DESIRABLE FOR DISTURBANCES ATTENUATION

VGL ATTITUDE DYNAMICS

- ROTATIONAL EQUATIONS OF VGL
  ADDED TO SIMULATION MODEL

- VGL MOMENT OF INERTIA

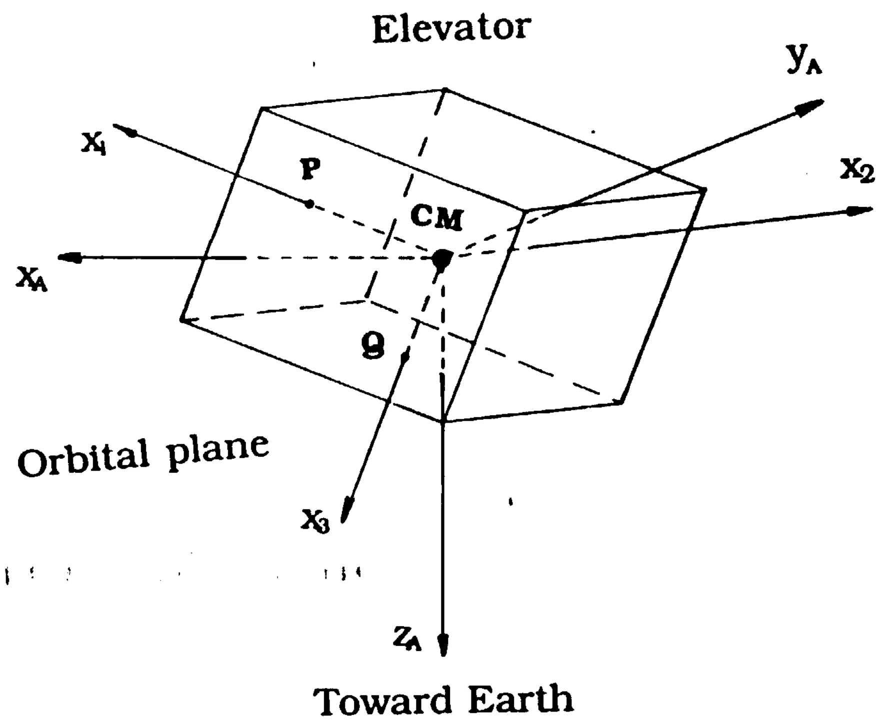
  $I_1 = 608$ KG-M^2

  $I_2 = 763$ KG-M^2

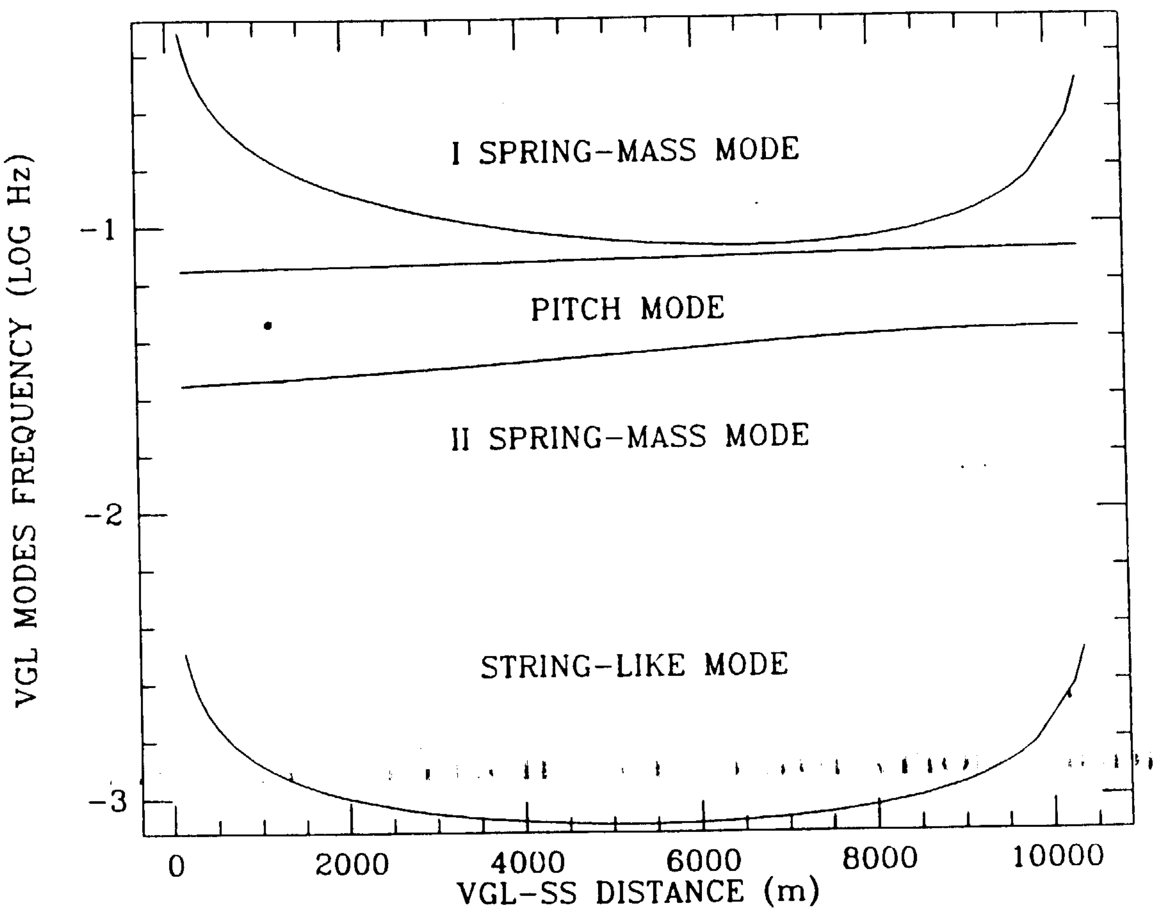
  $I_3 = 808$ KG-M^2

- VGL DIMENSIONS

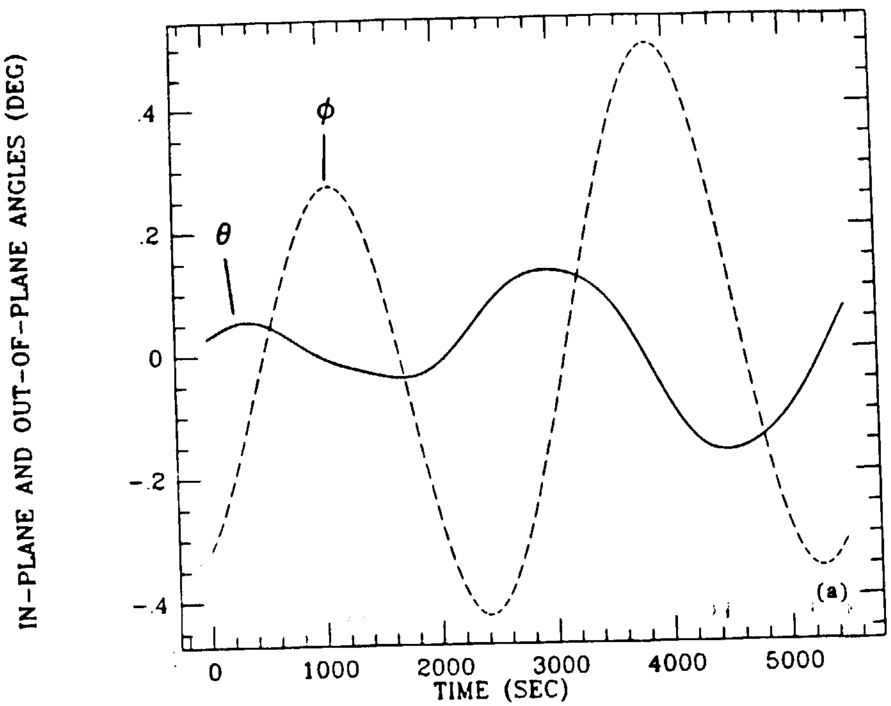
IN-FLIGHT	1.7 M
VERTICAL	1.3 M
OUT-OF-PLANE	1.2 M

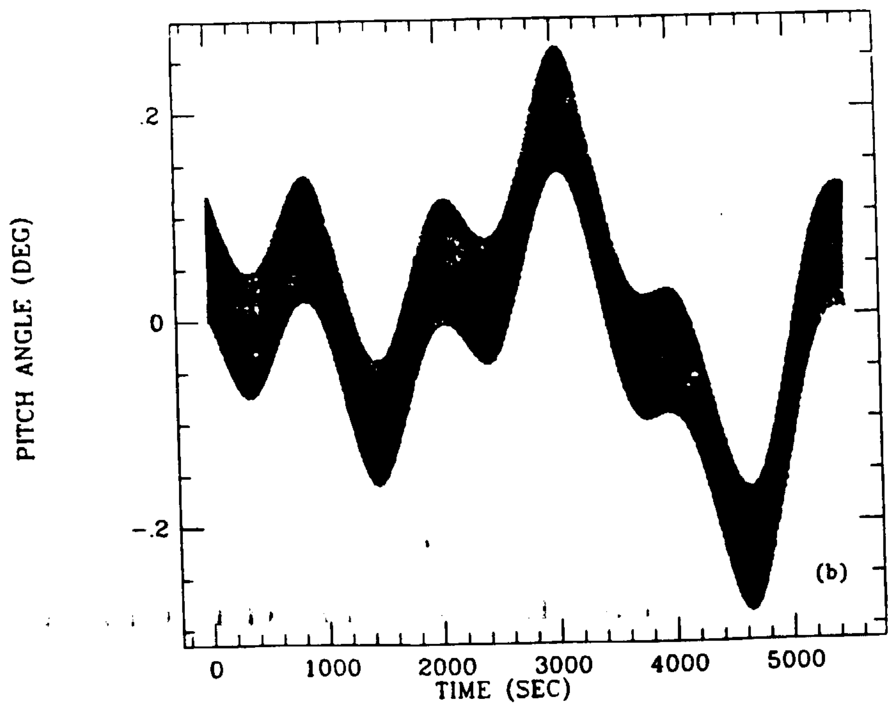


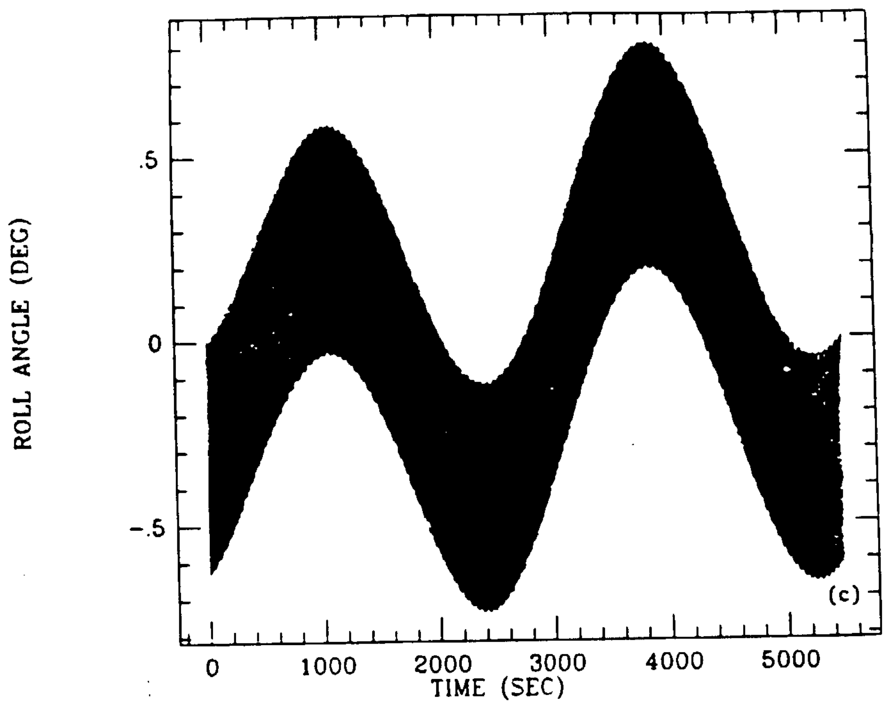
EIGENFREQUENCIES OF SIMULATION MODEL

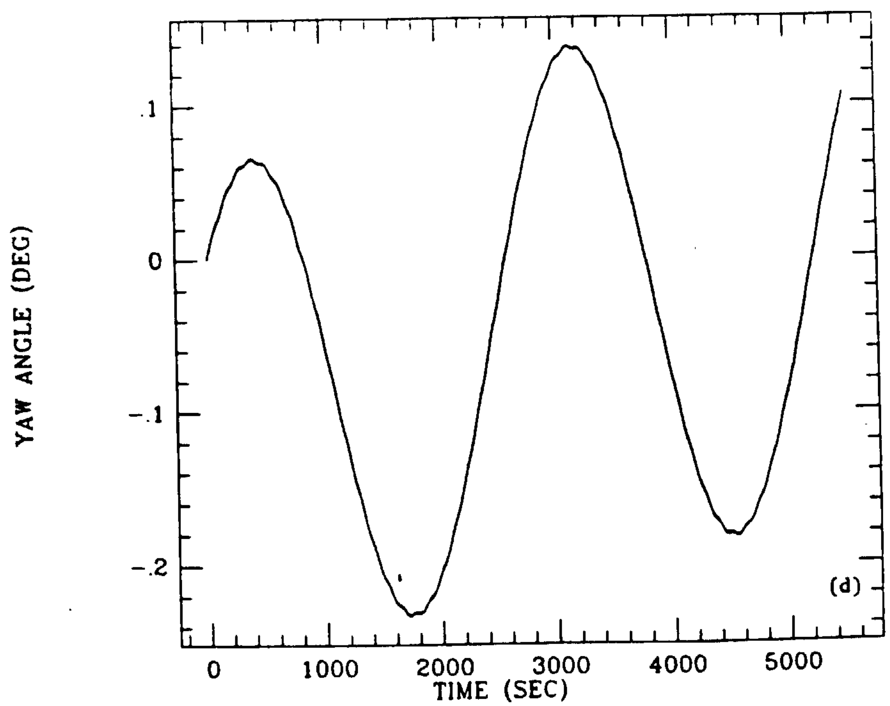


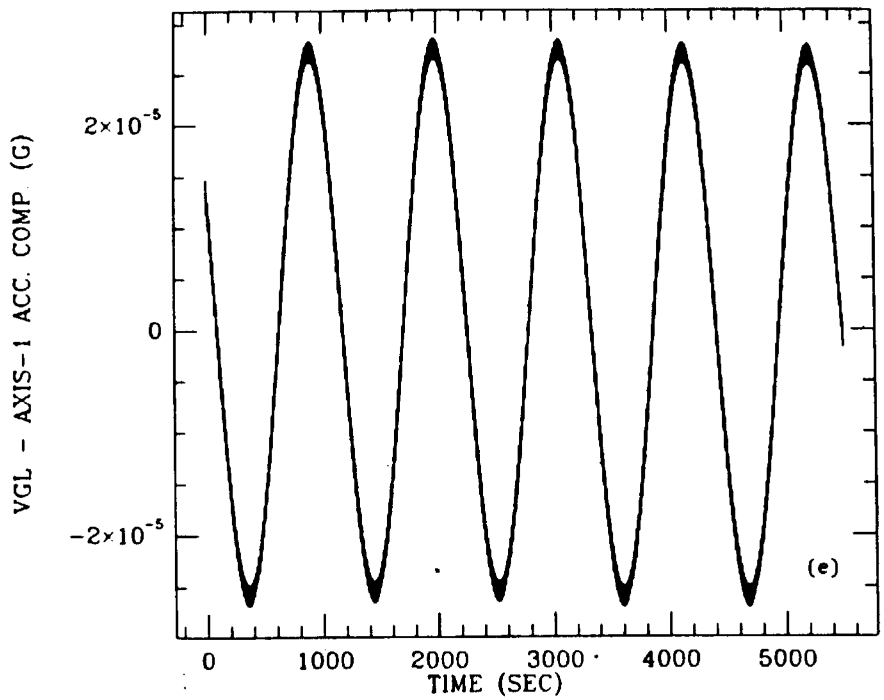
DYNAMIC RESPONSE OF VGL STATIONED AT 2667 M OFF SS

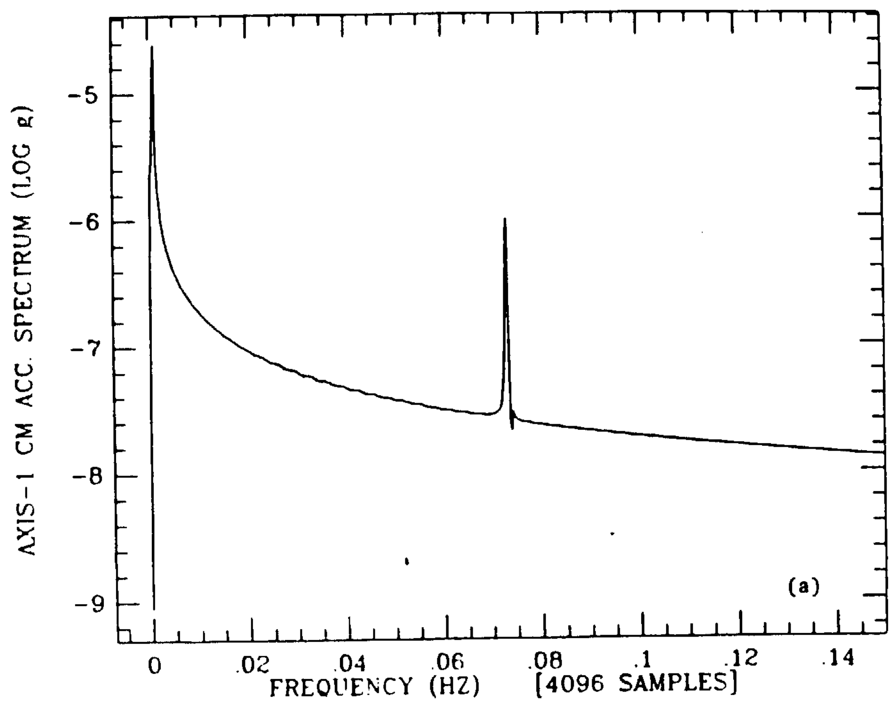


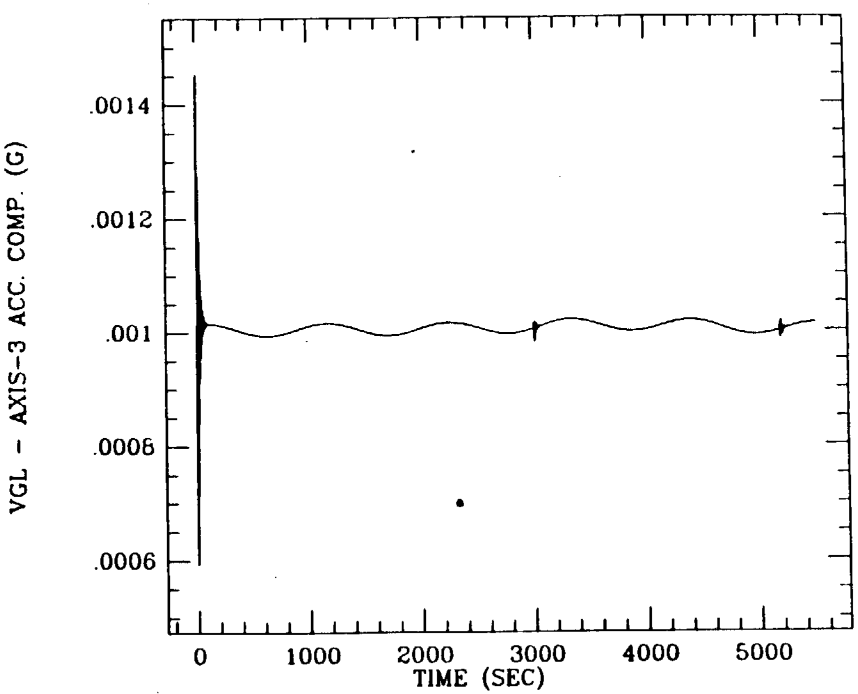



ROLL ANGLE (DEG)
.5
0
-.5
0
1000
2000
3000
4000
5000
TIME (SEC)
(c)

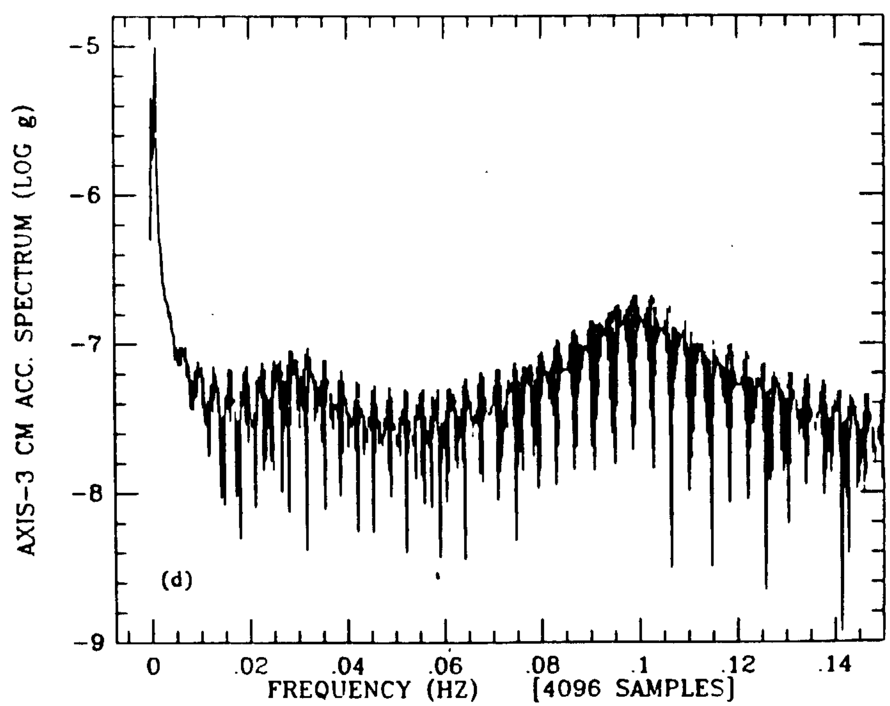

YAW ANGLE (DEG)
.1
0
-.1
-.2
0
1000
2000
3000
4000
5000
TIME (SEC)
(d)


VGL - AXIS-1 ACC. COMP. (G)
2×10⁻⁵
0
−2×10⁻⁵
0
1000
2000
3000
4000
5000
TIME (SEC)
(e)

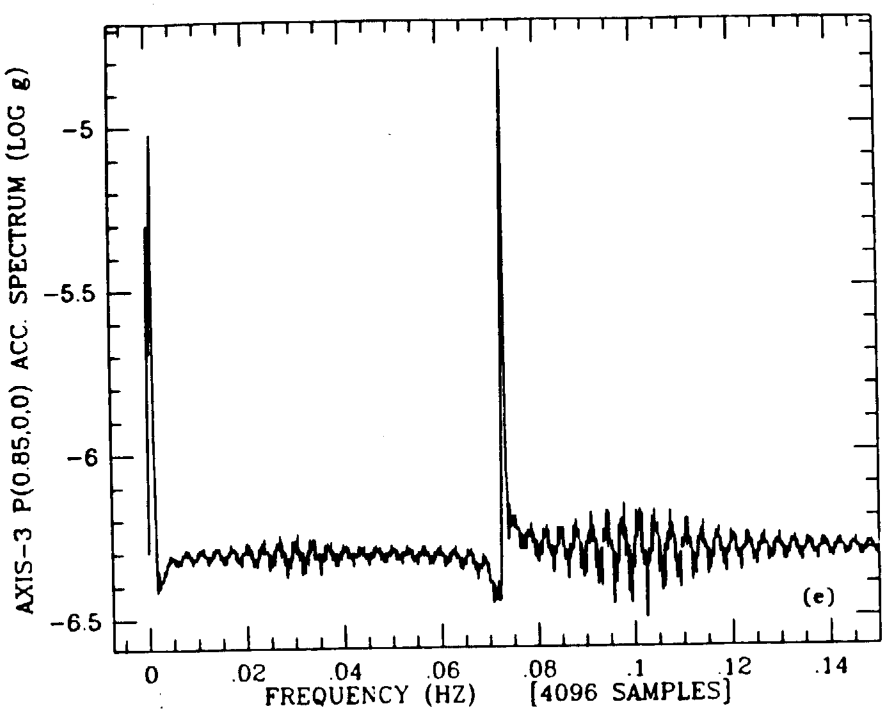

AXIS-1 CM ACC. SPECTRUM (LOG g)
−5
−6
−7
−8
−9
0
.02
.04
.06
.08
.1
.12
.14
FREQUENCY (HZ)
[4096 SAMPLES]
(a)

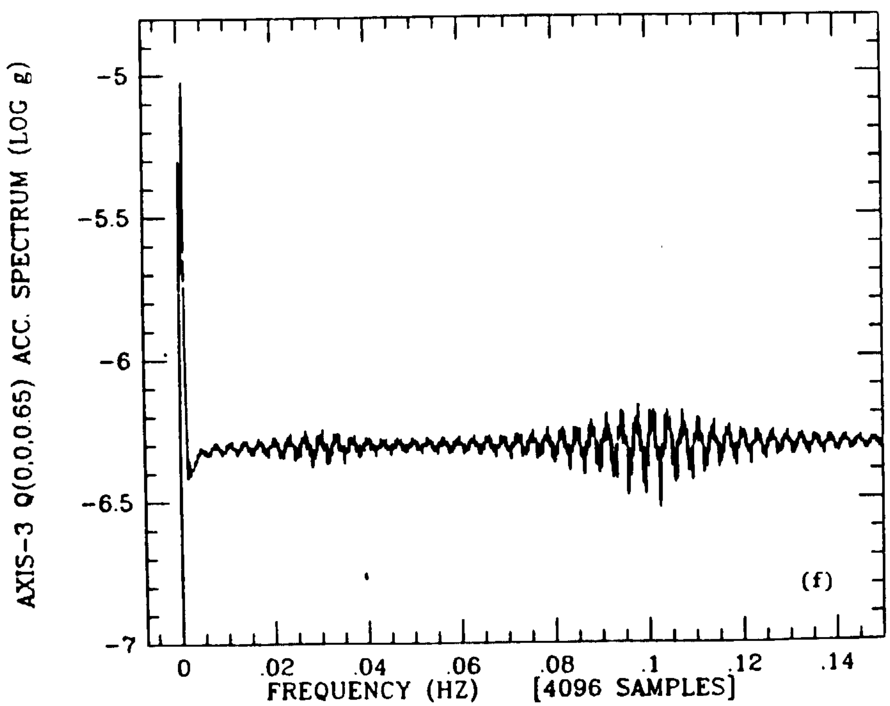


VGL - AXIS-3 ACC. COMP. (G)
.0014
.0012
.001
.0008
.0006
0
1000
2000
3000
4000
5000
TIME (SEC)



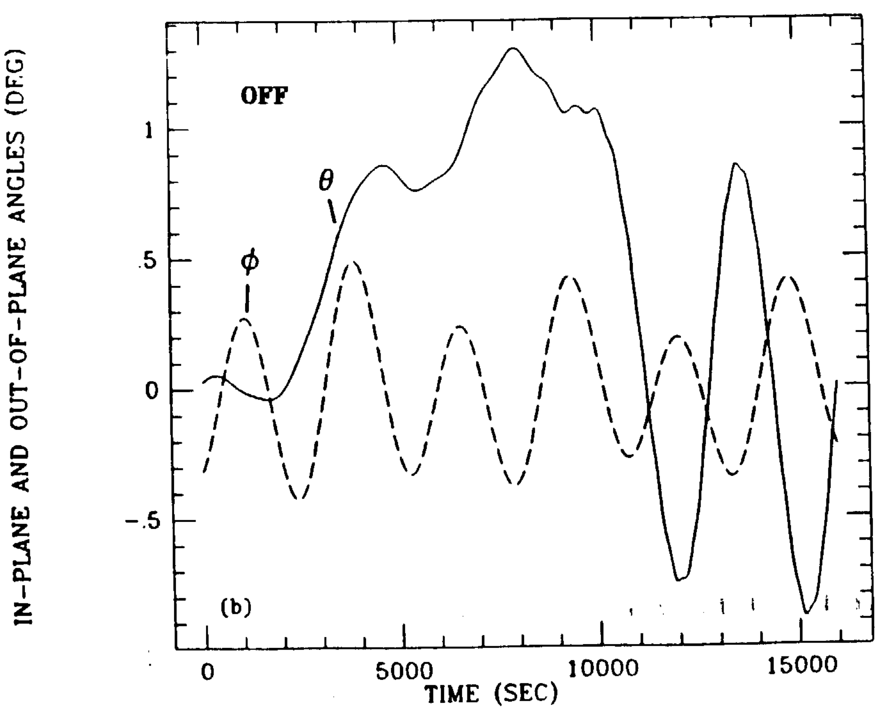
AXIS-3 CM ACC. SPECTRUM (LOG g)
-5
-6
-7
-8
-9
(d)
0
.02
.04
.06
.08
.1
.12
.14
FREQUENCY (HZ) [4096 SAMPLES]

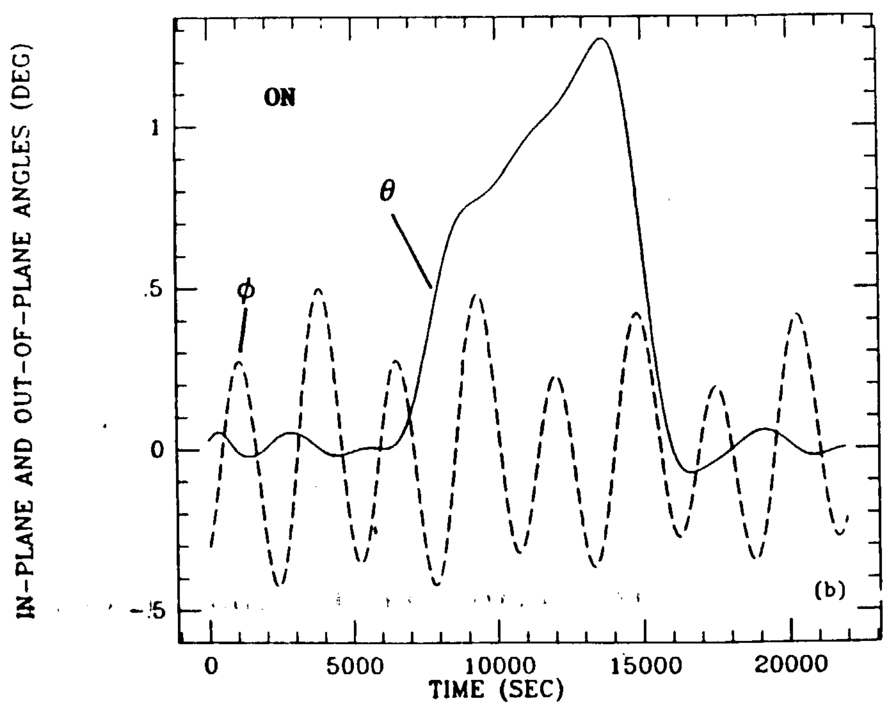

AXIS-3 P(0.85,0,0) ACC. SPECTRUM (LOG g)
-5
-5.5
-6
-6.5
0
.02
.04
.06
.08
.1
.12
.14
FREQUENCY (HZ)
[4096 SAMPLES]
(e)

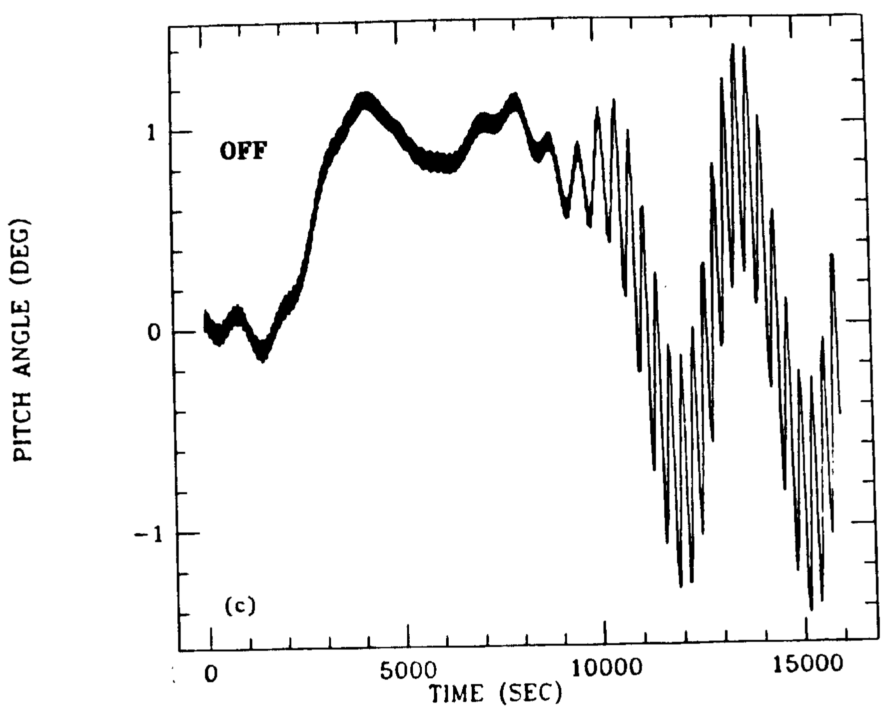

AXIS-3 Q(0,0,0.65) ACC. SPECTRUM (LOG g)
-5
-5.5
-6
-6.5
-7
0
.02
.04
.06
.08
.1
.12
.14
FREQUENCY (HZ)
[4096 SAMPLES]
(f)

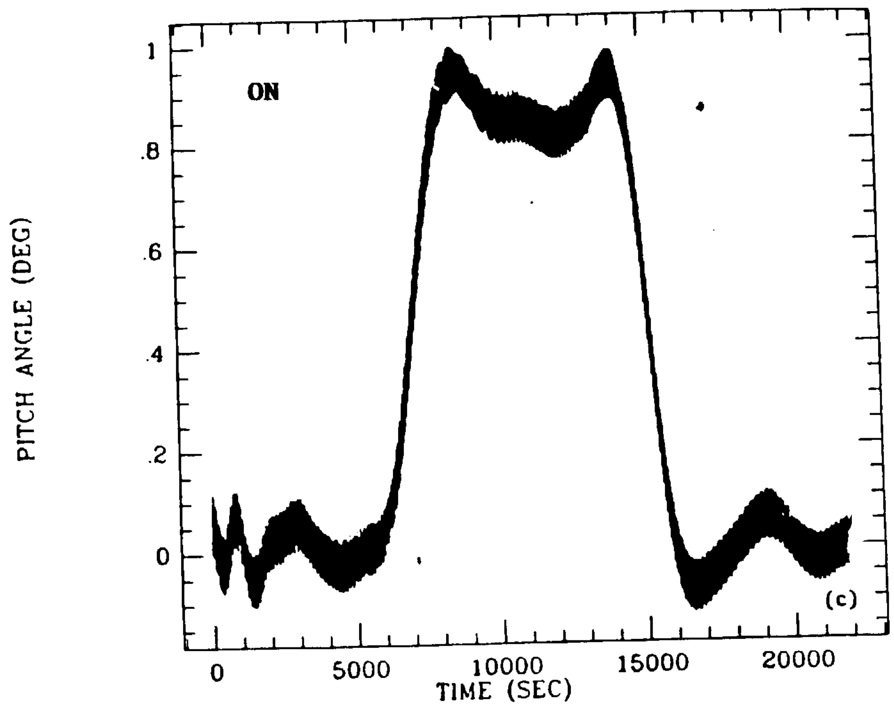
VGL CRAWLING MANEUVERS FROM 2667 M TO 10242 M

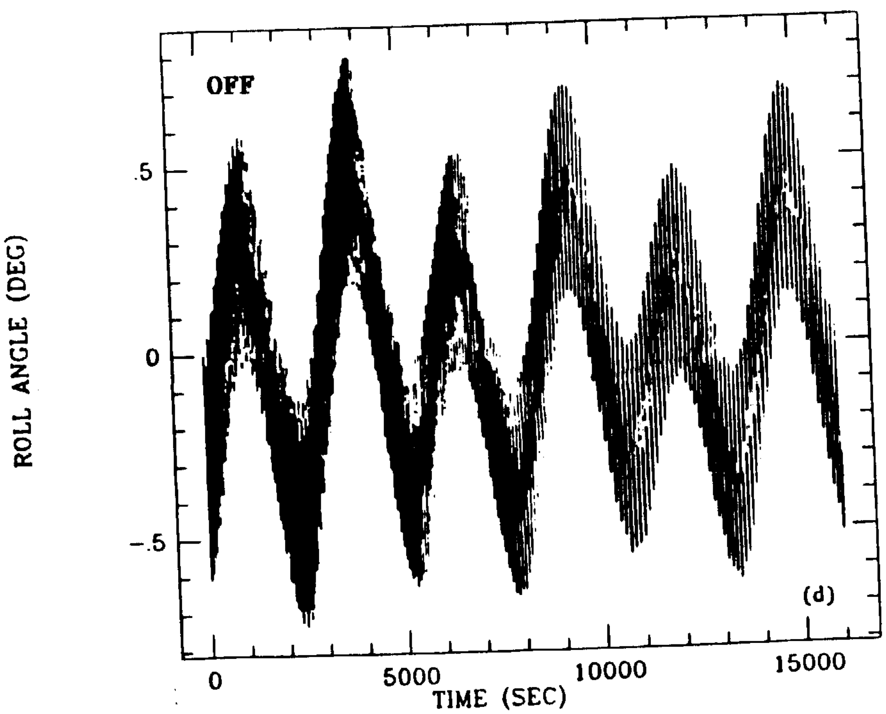
- LIBRATIONAL/LATERAL DAMPERS OFF VERSUS DAMPERS ON

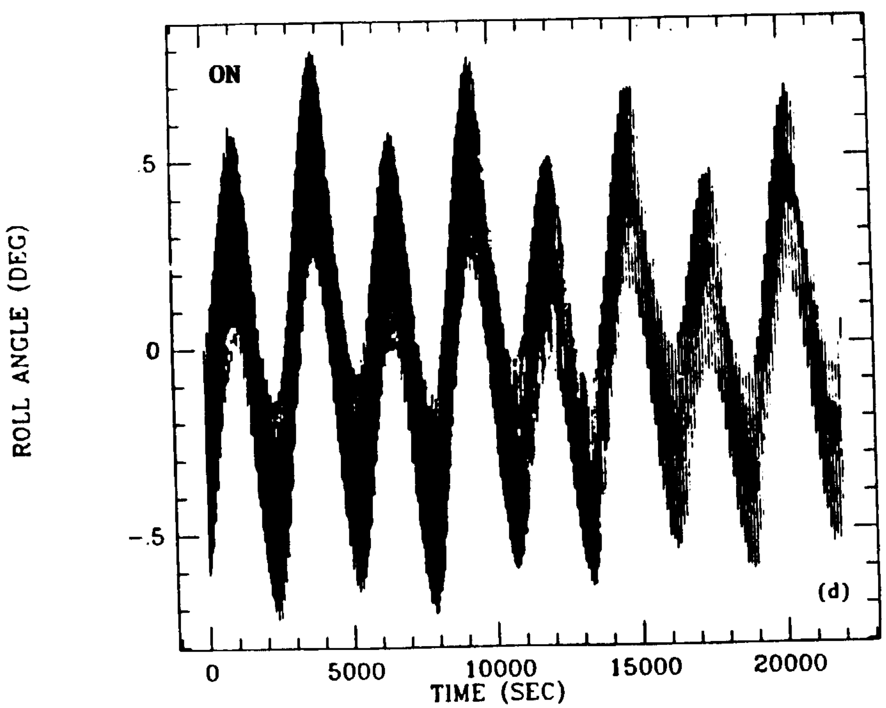


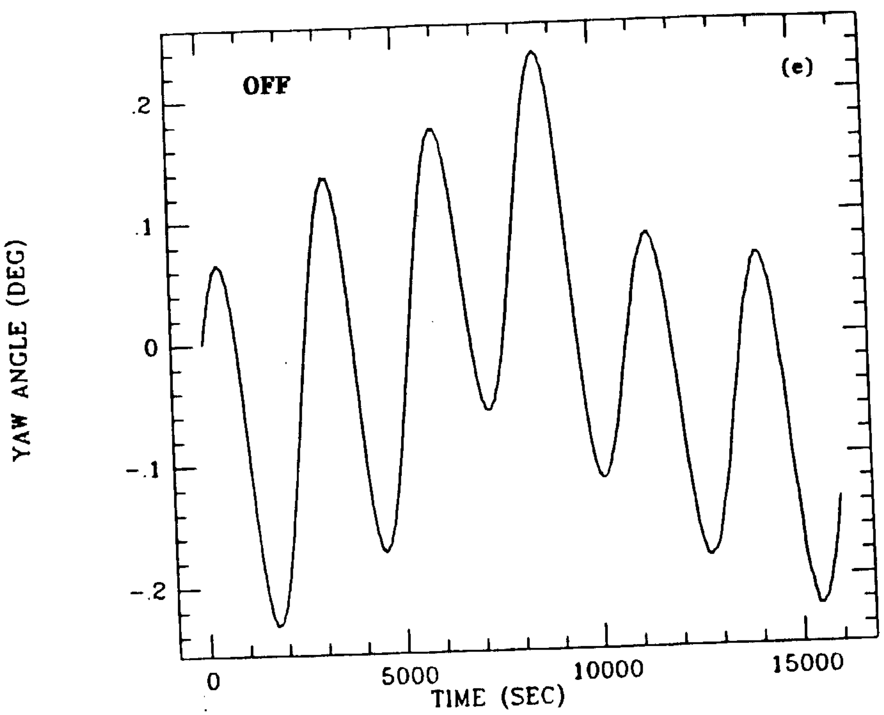


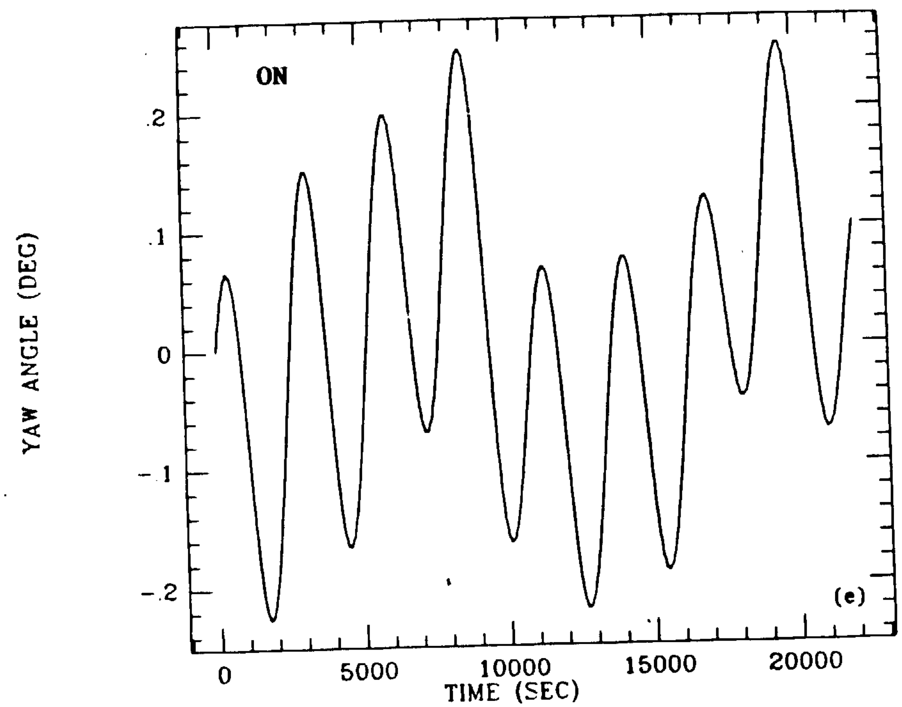

PITCH ANGLE (DEG)
OFF
(c)
1
0
-1
0
5000
10000
15000
TIME (SEC)

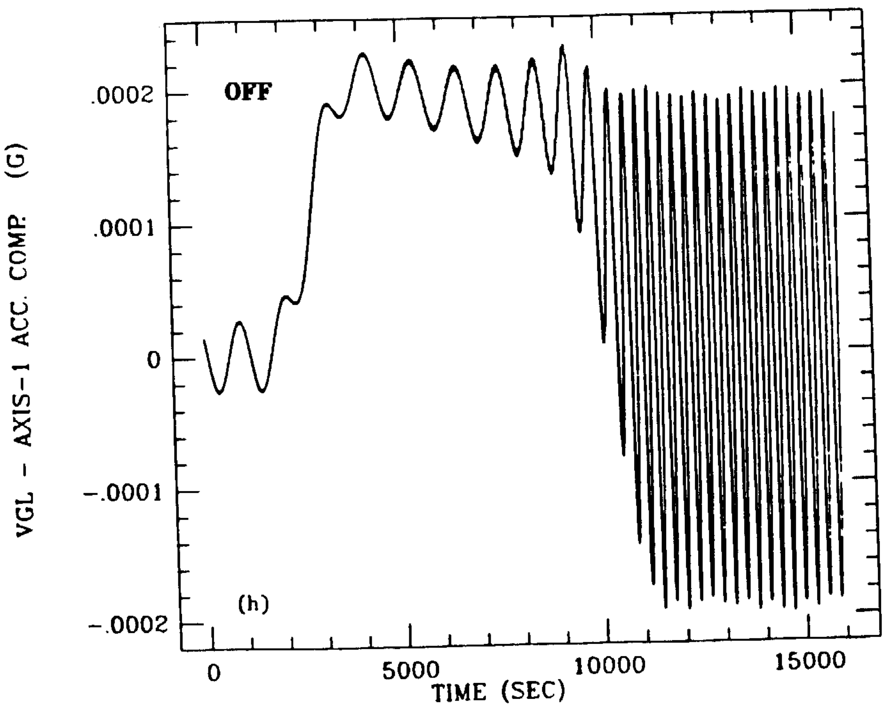

PITCH ANGLE (DEG)
ON
(c)
1
.8
.6
.4
.2
0
0
5000
10000
15000
20000
TIME (SEC)


OFF
ROLL ANGLE (DEG)
.5
0
-.5
0
5000
10000
15000
TIME (SEC)
(d)

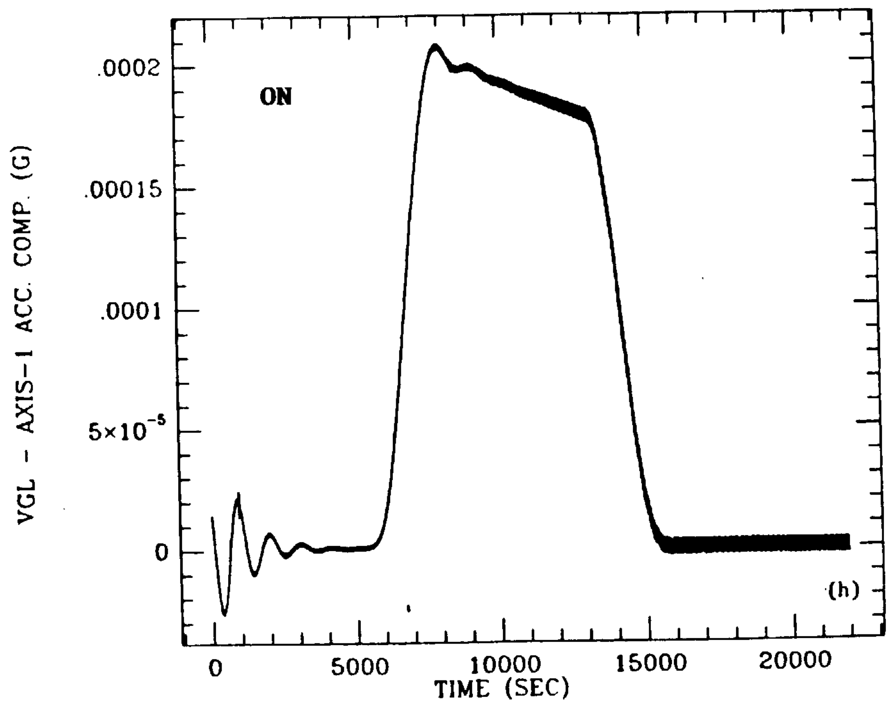

ON
ROLL ANGLE (DEG)
.5
0
-.5
0
5000
10000
15000
20000
TIME (SEC)
(d)


OFF
(e)
YAW ANGLE (DEG)
TIME (SEC)
.2
.1
0
-.1
-.2
0
5000
10000
15000

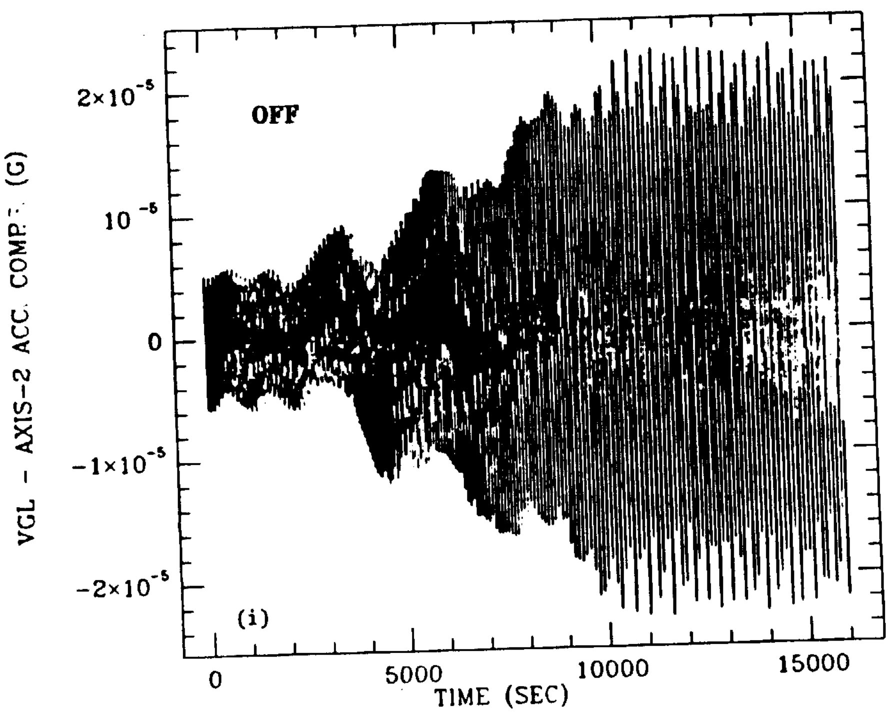

ON
(e)
YAW ANGLE (DEG)
TIME (SEC)
.2
.1
0
-.1
-.2
0
5000
10000
15000
20000

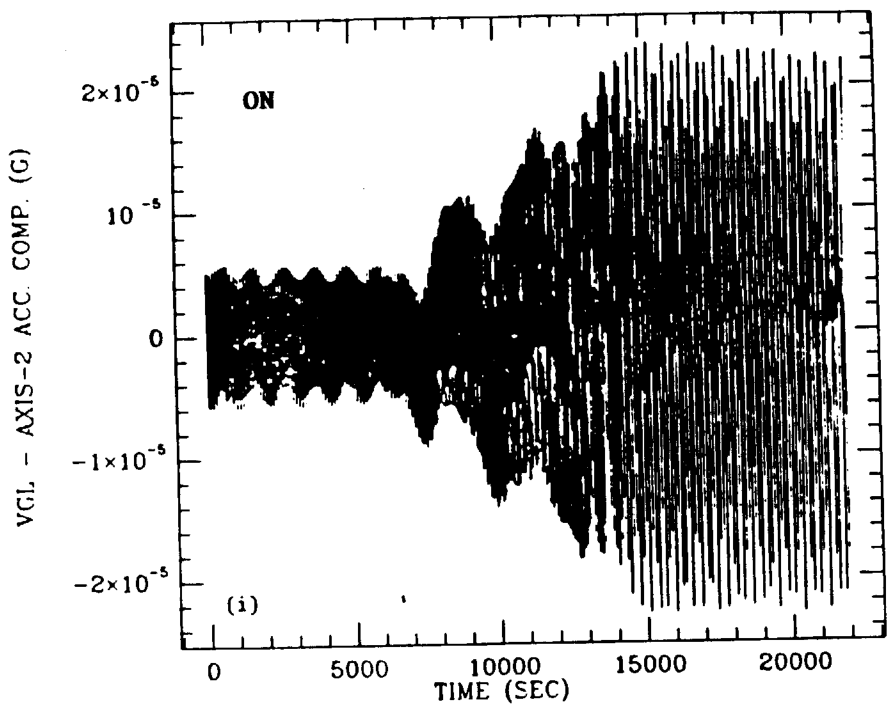


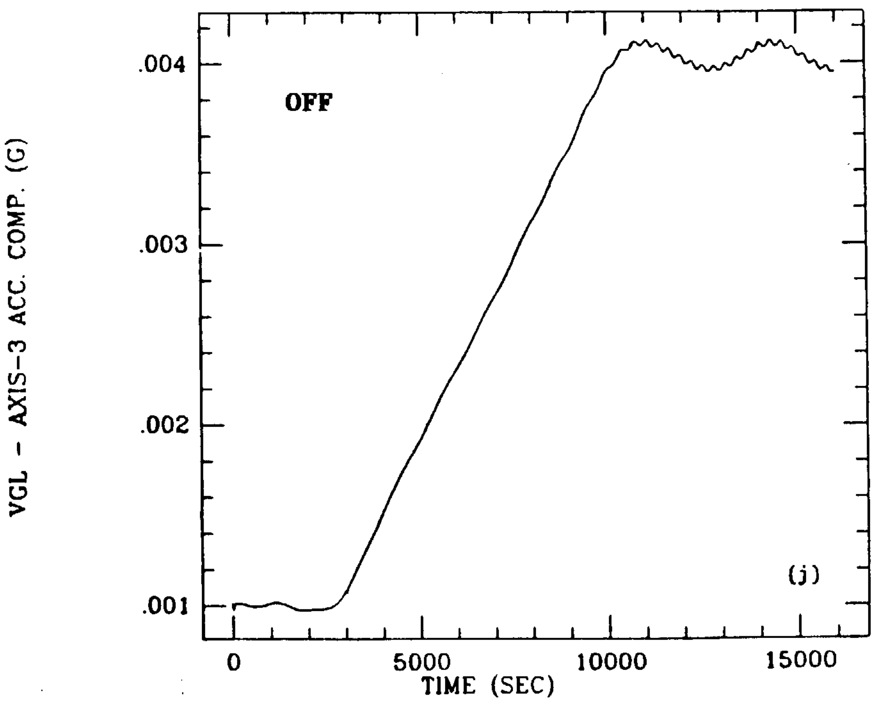
OFF
(h)
VGL - AXIS-1 ACC. COMP (G)
.0002
.0001
0
-.0001
-.0002
0
5000
10000
15000
TIME (SEC)



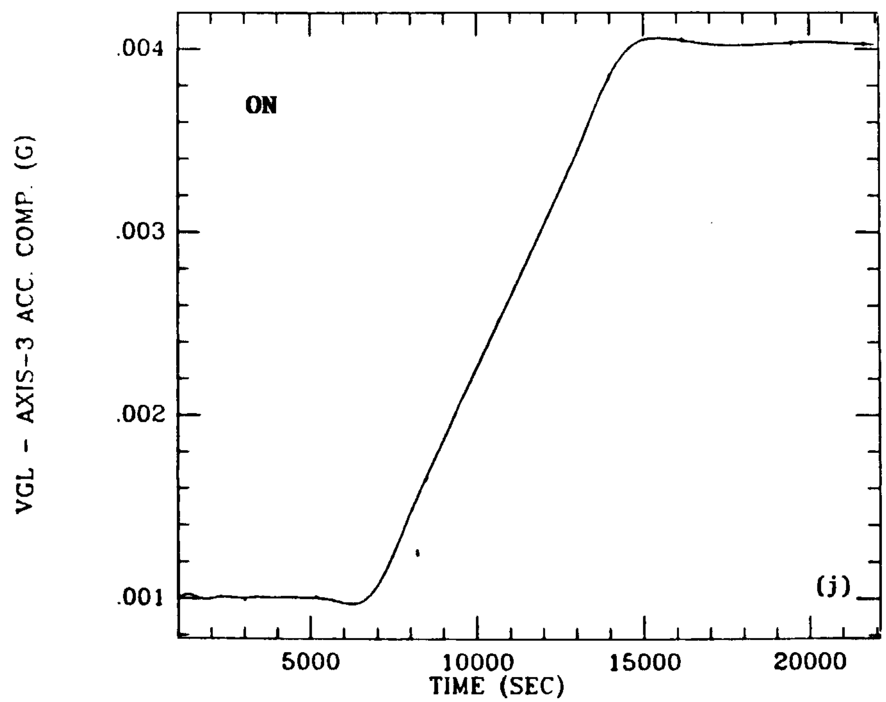
ON
(h)
VGL - AXIS-1 ACC. COMP. (G)
.0002
.00015
.0001
5×10⁻⁵
0
0
5000
10000
15000
20000
TIME (SEC)


OFF
(i)
VGL - AXIS-2 ACC. COMP. (G)
2×10⁻⁵
10⁻⁵
0
-1×10⁻⁵
-2×10⁻⁵
0
5000
10000
15000
TIME (SEC)


ON
(i)
VGL - AXIS-2 ACC. COMP. (G)
2×10⁻⁵
10⁻⁵
0
-1×10⁻⁵
-2×10⁻⁵
0
5000
10000
15000
20000
TIME (SEC)



VGL - AXIS-3 ACC. COMP. (G)
.004
.003
.002
.001
OFF
(j)
0
5000
10000
15000
TIME (SEC)



VGL - AXIS-3 ACC. COMP. (G)
.004
.003
.002
.001
ON
(j)
5000
10000
15000
20000
TIME (SEC)

CONCLUSIONS ON VGL ATTITUDE DYNAMICS

- EXPERIMENTAL AREA WITH SUITABLE ACCELERATION LEVELS IS LIMITED BY ATTITUDE DYNAMICS OF VGL

- CRAWLING MANEUVERS
  - –LIBRATIONAL/LATERAL DAMPERS QUITE EFFECTIVE IN ABATING LOW FREQUENCY DISTURBANCES
  - –ATTITUDE DAMPERS REQUIRED FOR ABATING (HIGHER FREQUENCY) ATTITUDE OSCILLATIONS DURING TRANSFER MANEUVERS

SAO SUBCONTRACT STATUS